Robust and automatic dual wavelength-based endpointing for consistent batch-to-batch plasma etching of InP-based lasers

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Outline

- Introduction
- Compound Semiconductor manufacturing chain and optical metrology
- Experimental for InP laser structures
- Plasma etching and endpointing
- Summary & Outlook

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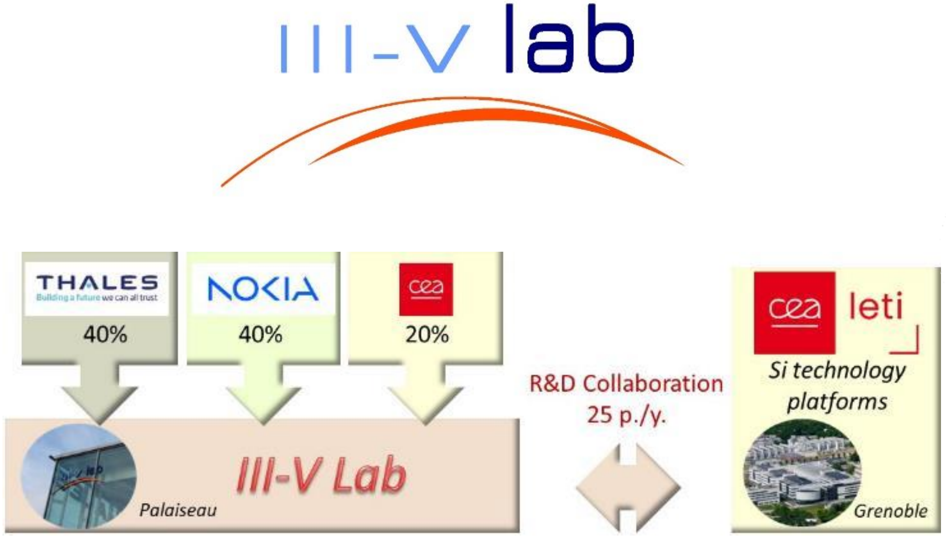
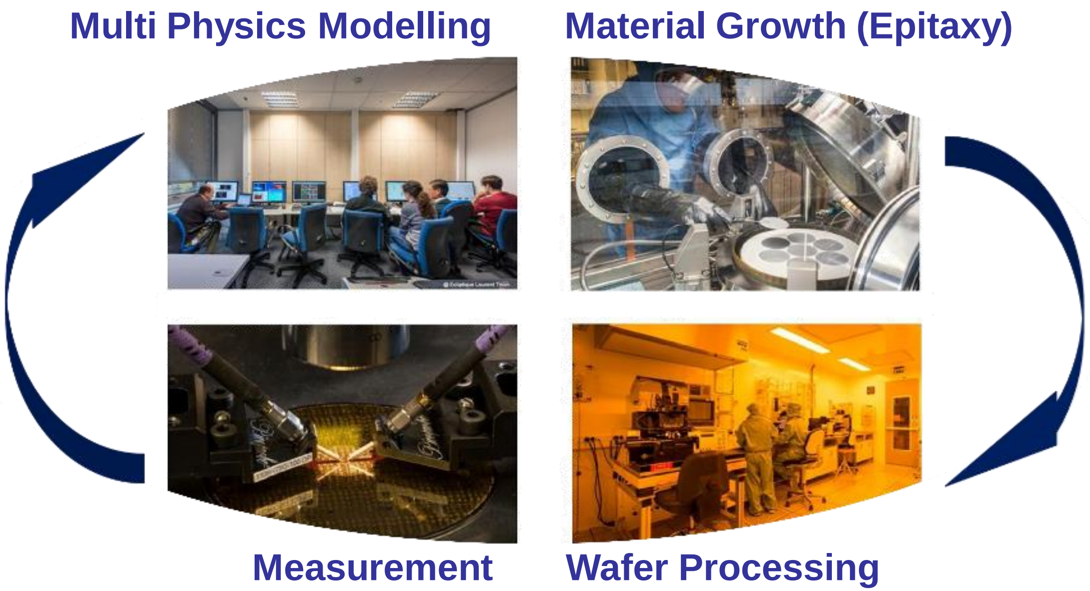
Who we are ...

- **III-V Lab: an Economic Interest Group between Thales, Nokia and CEA/Leti**
- 120 research staff - 20 PhD students
- Focus on III-V semiconductors technologies development and their integration with Silicon circuits and micro-systems

IIIA 3A	IVA 4A	VA 5A
5 4000 B Boron 10.811	6 graphite 3825 SP C Carbon 12.011	7 -195.798 N Nitrogen 14.007
13 2519 Al Aluminum 26.982	14 3265 Si Silicon 28.086	15 white 280.5 P Phosphorus 30.974
31 2204 Ga Gallium 69.732	32 2833 Ge Germanium 72.61	33 616 SP As Arsenic 74.922
49 2072 In Indium 114.818	50 2602 Sn Tin 118.71	51 1587 Sb Antimony 121.760

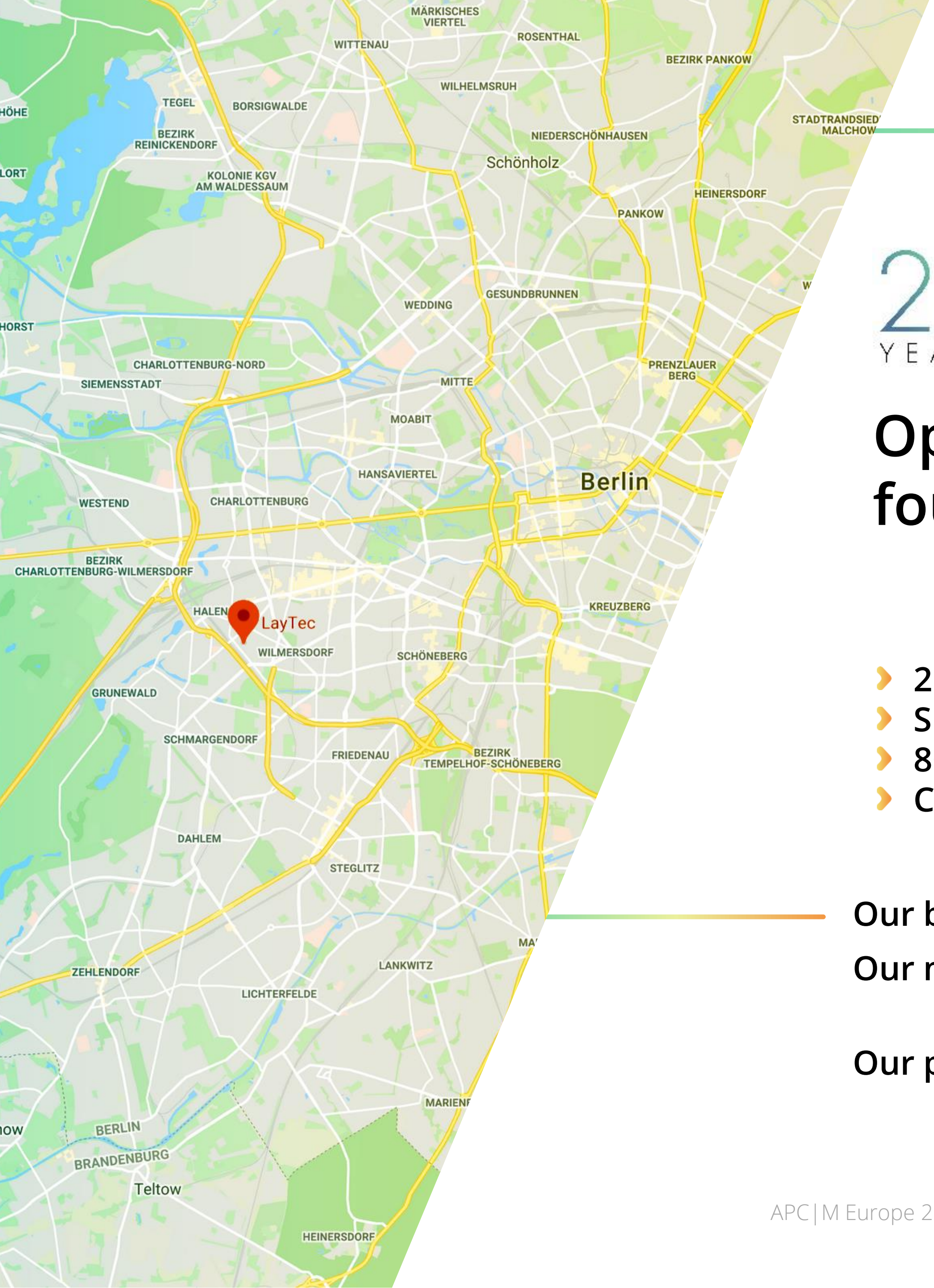




NOKIA

leti
cea tech

THALES



25 YEARS LAYTEC

Optical Metrology Company founded 1999 in Berlin

- 25 years old
- Spin-off of TU Berlin
- 80+ employees
- Close to 4000 systems sold
- Operating worldwide
- Member of Nynomic group

NYNOMIC
THE PHOTONICS GROUP

Our business:	Process-integrated optical metrology
Our markets:	Compound semiconductor and thin-film industry & academia incl. lighting, laser, PV, glass coating …
Our products:	in-situ metrology for epi, Wafer mapper, in-situ metrology for dry etch

Integrated metrology for various industries and markets

… nobody knows the LayTec products, but everyone uses a lot of things, for which they are necessary!

Laser

LED/µLED

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Functional glass

Power devices

Photovoltaics

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Optical metrology along the semiconductor manufacturing chain

costs

value

risks

high costs

high value generation

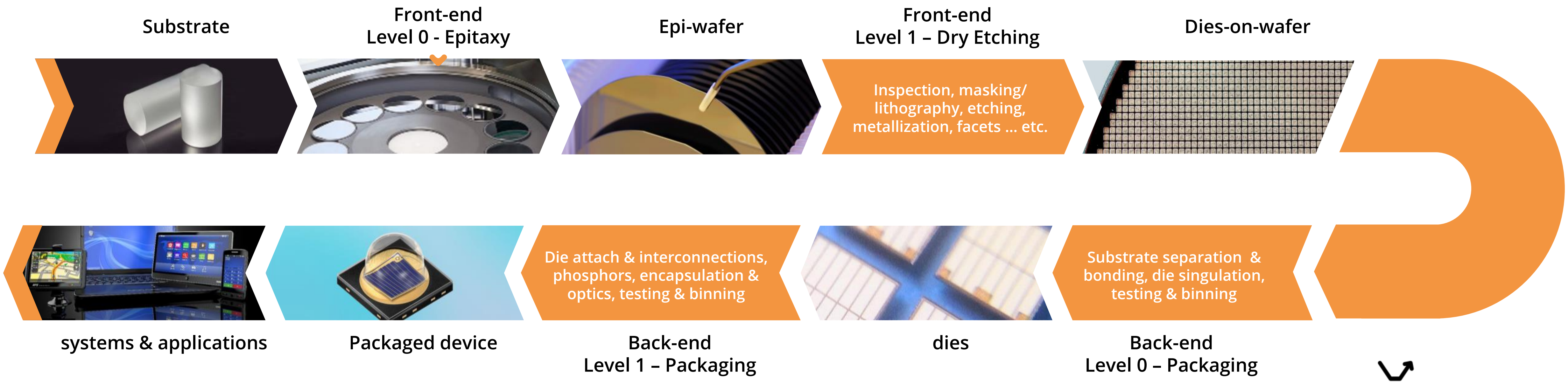
temperature
thickness
composition

unknown
uniformity

maintain or
destroy value

wrong
etch stop

{ wafer-to-wafer
run-to-run
system-to-system



Substrate

Front-end
Level 0 - Epitaxy

Epi-wafer

Front-end
Level 1 – Dry Etching

Inspection, masking/
lithography, etching,
metallization, facets … etc.

Dies-on-wafer

Substrate separation &
bonding, die singulation,
testing & binning

Back-end
Level 0 – Packaging

dies

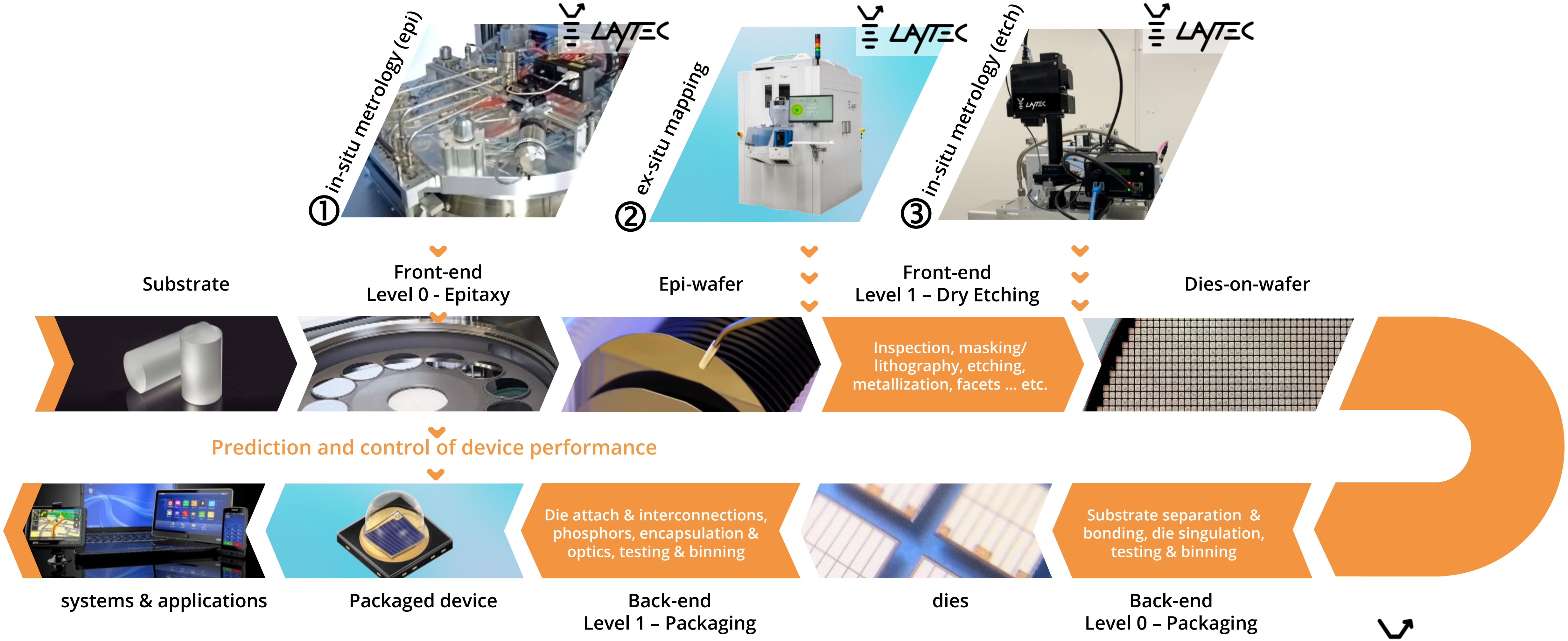
Die attach & interconnections,
phosphors, encapsulation &
optics, testing & binning

Back-end
Level 1 – Packaging

Packaged device

systems & applications

Optical metrology along the semiconductor manufacturing chain



① in-situ metrology (epi)

② ex-situ mapping

③ in-situ metrology (etch)

Substrate

Front-end
Level 0 - Epitaxy

Epi-wafer

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Dies-on-wafer

Prediction and control of device performance

Substrate separation &
bonding, die singulation,
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Back-end
Level 0 – Packaging

dies

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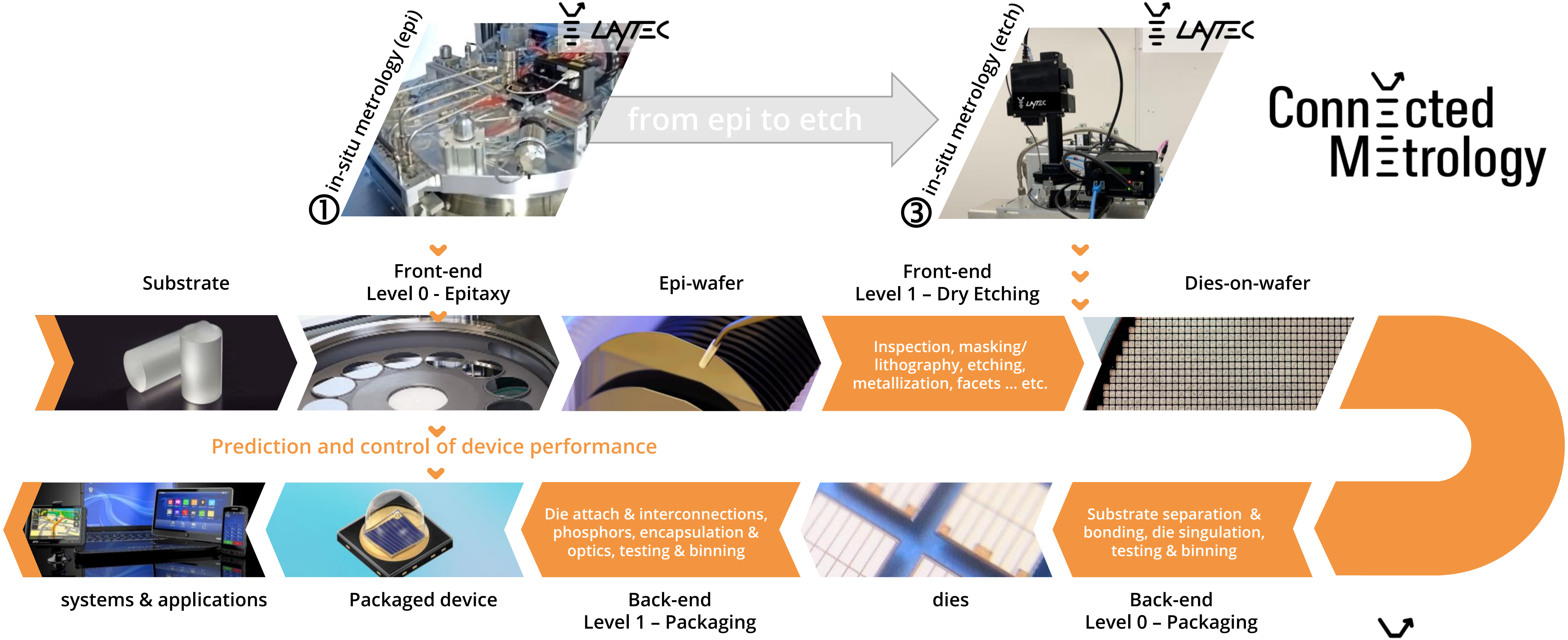
Packaged device

systems & applications

Optical metrology along the semiconductor manufacturing chain



① in-situ metrology (epi)

from epi to etch

③ in-situ metrology (etch)

Conn≡cted M≡trology

Substrate

Front-end
Level 0 - Epitaxy

Epi-wafer

Front-end
Level 1 – Dry Etching

Inspection, masking/
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systems & applications

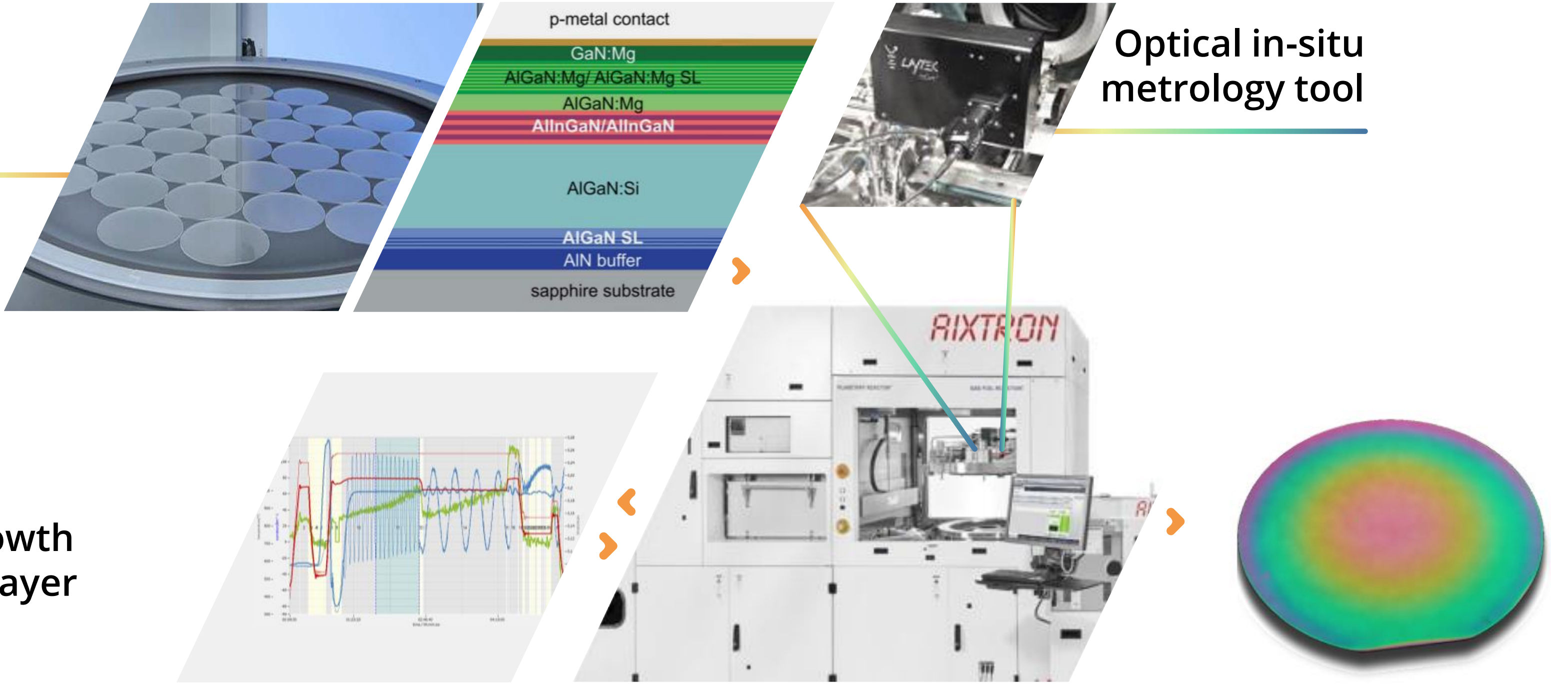
In-situ metrology for compound semiconductor epitaxy

Optical techniques

- Pyrometry
- Reflectometry
- Deflectometry

Substrate wafers + recipe for layer stack

Optical in-situ metrology tool



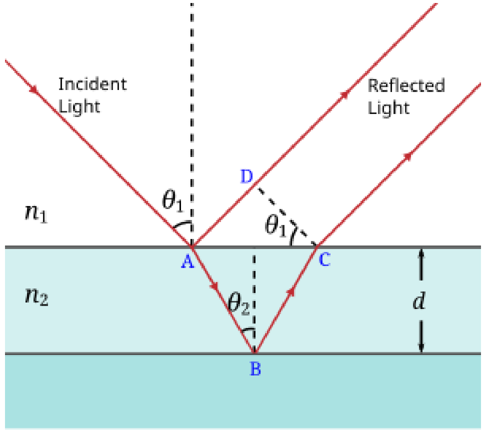
In-situ data for process control = monitoring and control of key growth parameters and layer properties

Characterized epi wafer

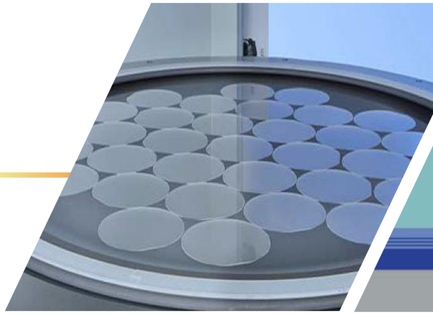
MOCVD equipment

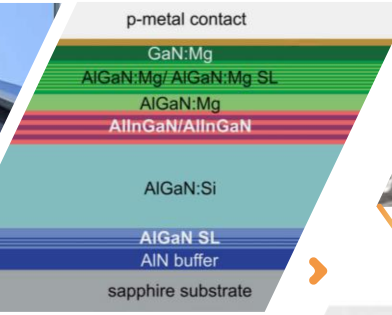
In-situ metrology for compound semiconductor epitaxy

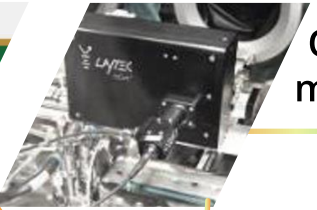
Thin film interference



Substrate wafers + recipe for layer stack

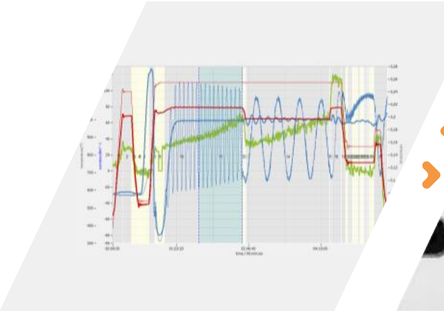




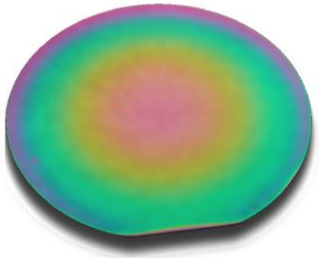


Optical in-situ metrology tool

In-situ data for process control = monitoring and control of key growth parameters and layer properties



MOCVD equipment

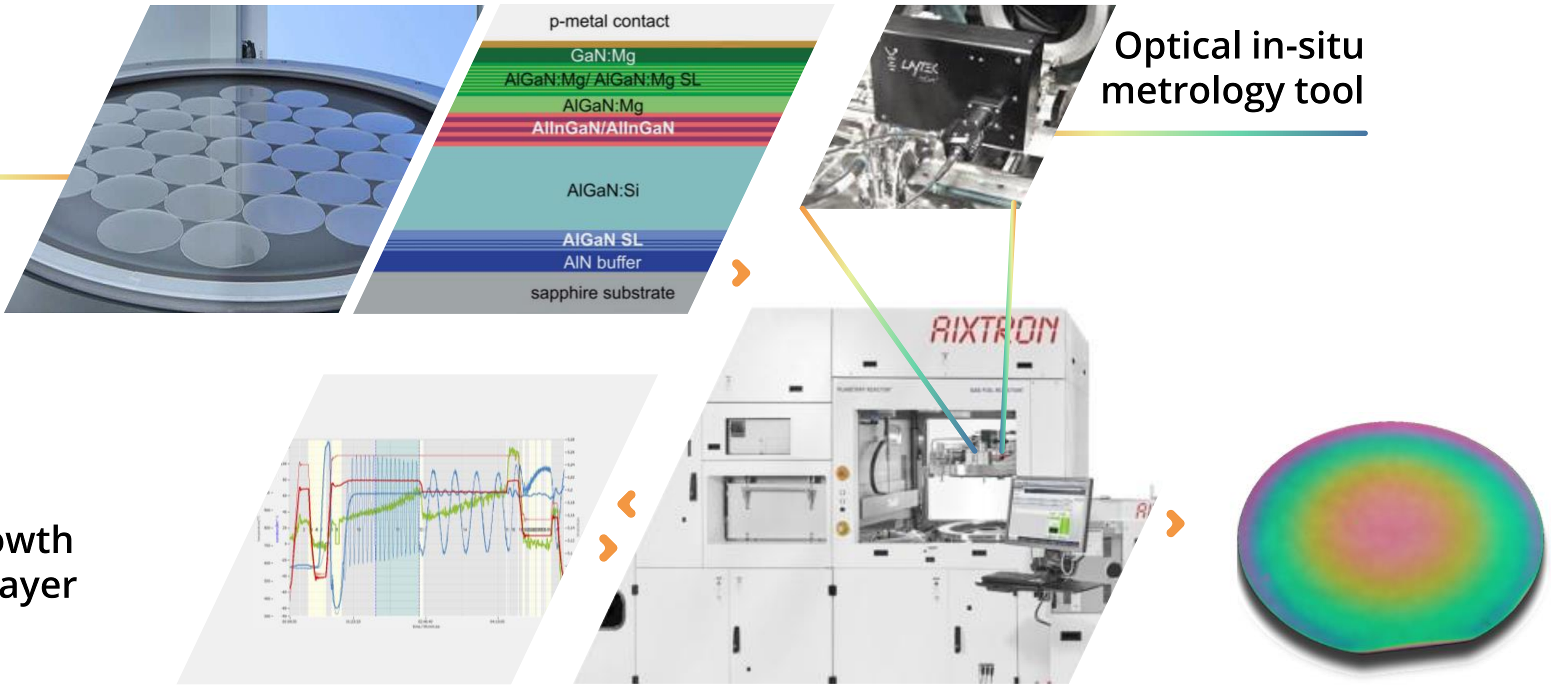


Characterized epi wafer

In-situ metrology for compound semiconductor epitaxy

Substrate wafers + recipe for layer stack

In-situ data for process control = monitoring and control of key growth parameters and layer properties



Optical in-situ metrology tool

MOCVD equipment

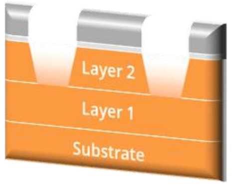
Characterized epi wafer

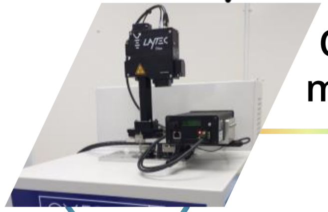
Measurement of

- growth rate
- layer thickness
- ternary composition
- surface morphology
- on-wafer uniformity
- …

In-situ metrology for dry etching processes

End point detection during dry etching processes





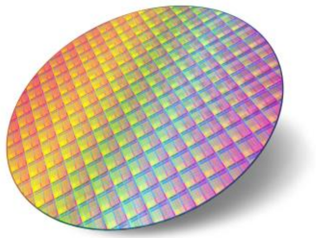
Optical in-situ metrology tool

Multi wavelength measurement of

- interface detection
- etch rate
- end pointing
- in ICP, RIE, ALE (Atomic Layer Etching)…

In-situ data for process control = monitoring and control of key etching parameters

Plasma etch equipment



In-spec etched wafer

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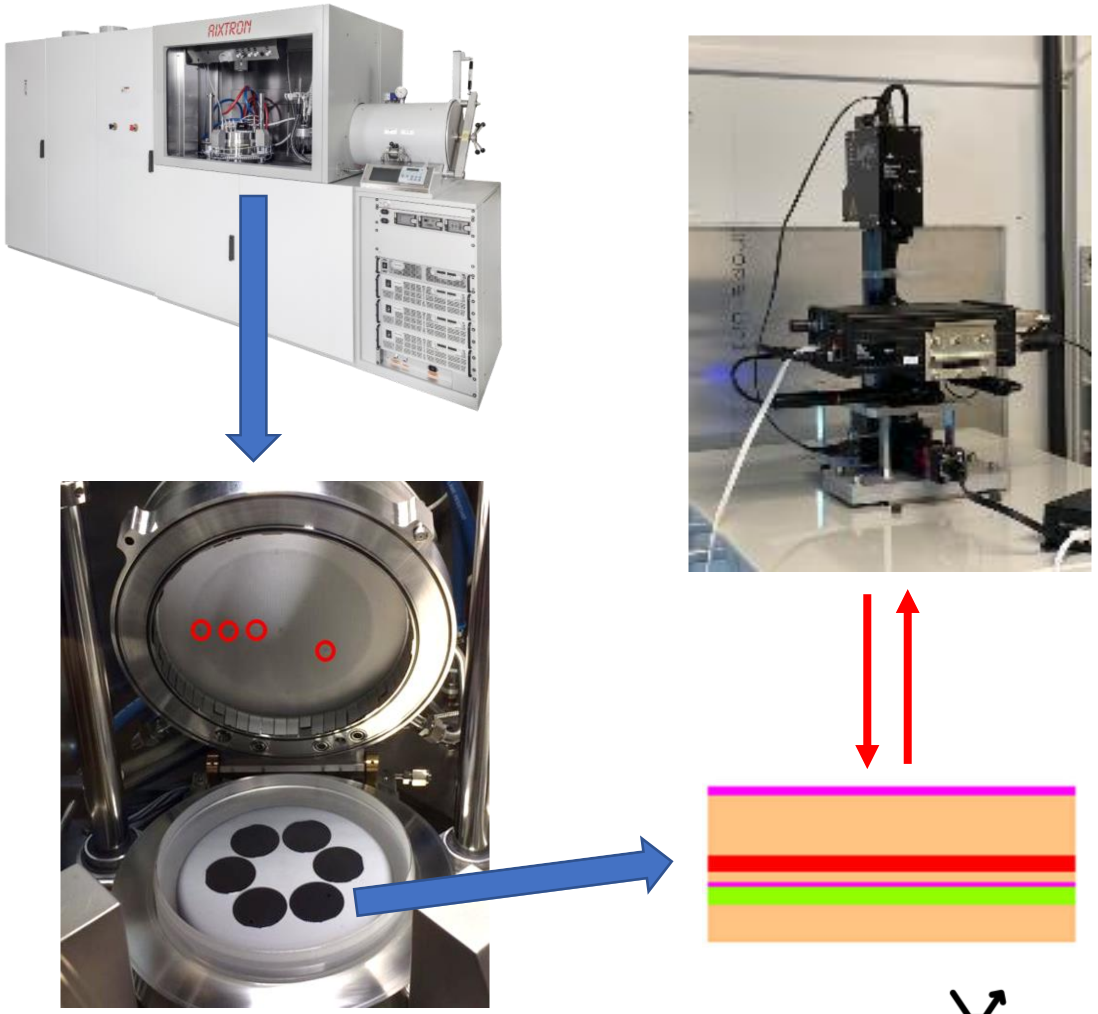
InP laser structures

- InP-based laser are needed for telecommunication and datacom
- Complex multi-layer structures grown in MOCVD
  - AIXTRON CCS 6x2“ / 3x3“ / 1x4 at III-V Lab
  - AlInGaAs MQW/barriers for O- and C-band
- Etching and patterning of the structures require a precise end point detection
  - Oxford Instruments ICP-RIE PlasmaLab 180
  - Two modes/chemistries:
    - RIE CH_4/H_2: very straight sidewalls, but very slow
    - RIE-ICP Cl_2/H_2: straight sidewalls w/ footing, but fast

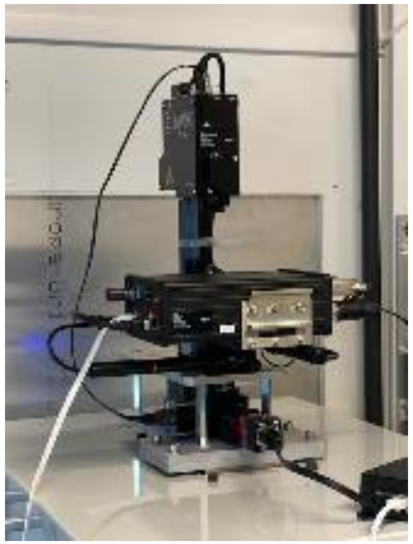
Growth

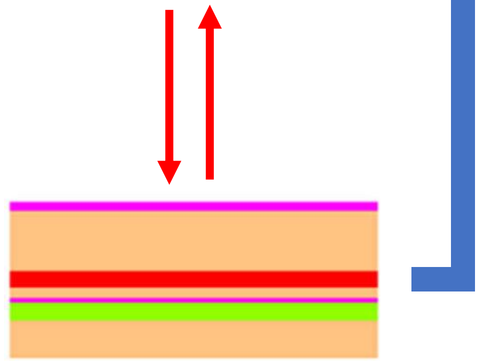
Etching

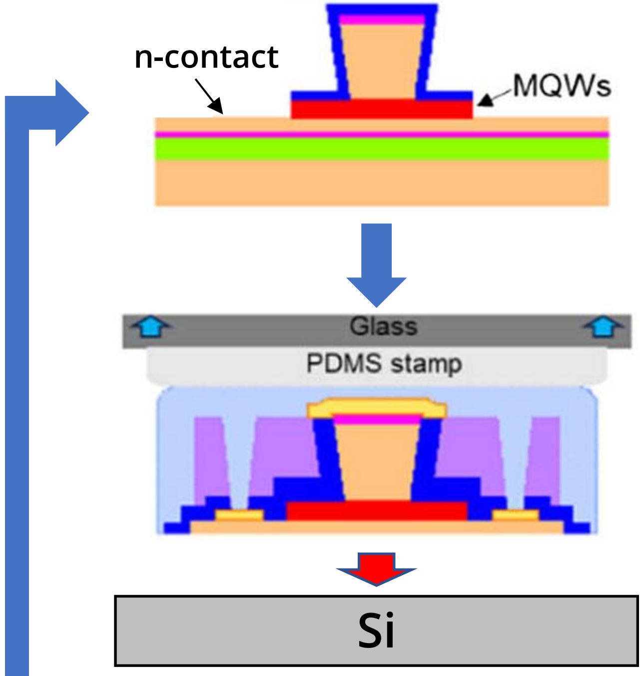


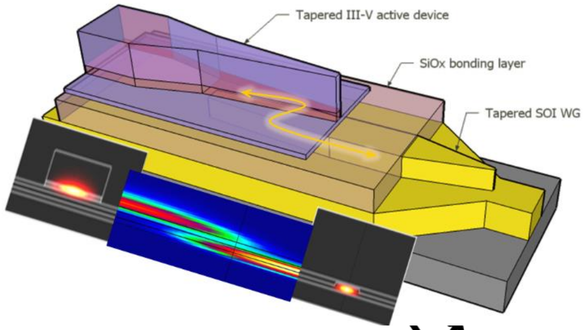
InP laser structures

- Application: III-V lasers on Si photonics circuitry platform
  - A very thin InP contact layer is used for evanescent coupling
  - III-V etching should be stopped precisely at the beggining of this layer
  - Thinning of this layer causes increase in series resitance
- High accuracy during etch process is mandatory
- In-situ metrology fo real-time end-pointing is a solution









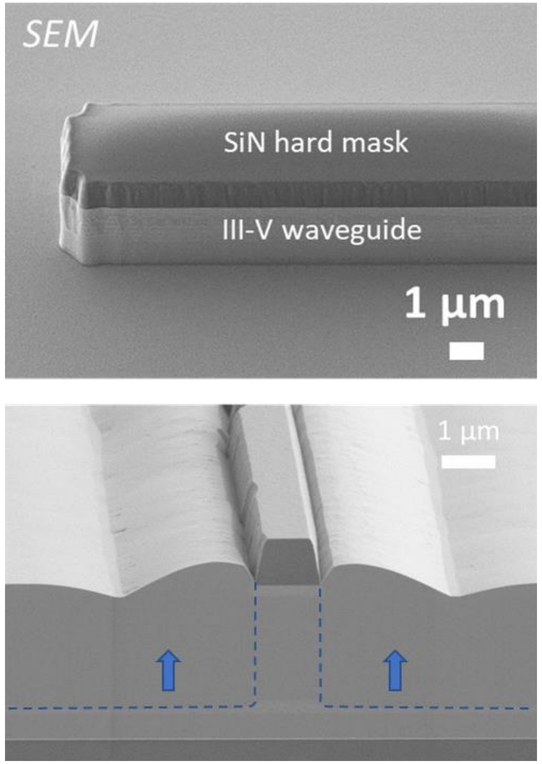
Challenges in InP laser fabrication

- Precise etching control of the complex hetero-structure
  - Total etch depth
  - Distance from an interface
  - Remaining thickness

  → **end-pointing**
- Requirements of smooth surfaces and facets
- Etch depth accurately controlled from a few nm to a few µm
- Time-based etching has limitations
- End Point Detection (EPD) offers advantages
  - OES (optical emission spectroscopy) measures indirectly interface crossings and changes of etched materials based on plasma emission changes
  - Reflectance based interferometry measures directly interface positions and residual layer thicknesses “on the wafers” and can endpoint within layers

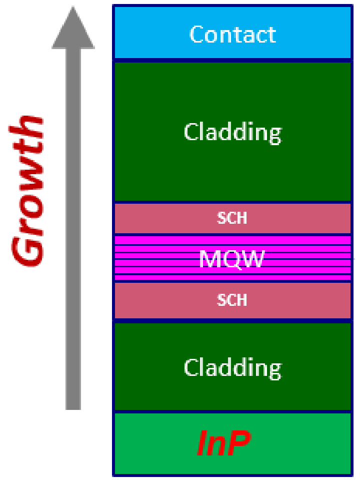
But, is interferometry based EPD suitable and precise enough for InP laser etch thickness control using ICP ?

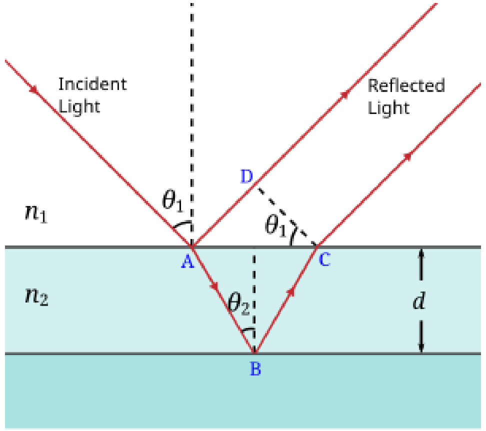
Example of SEM cross section of Ridge Waveguide



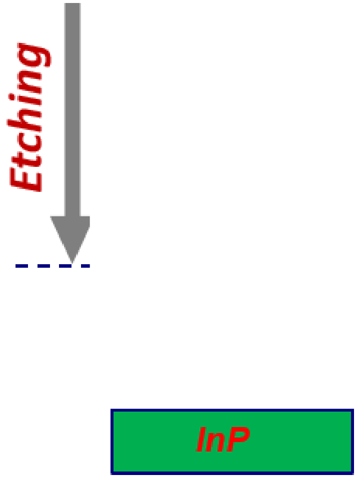
Growth and etching of InP-based laser structures

Schematic layer stack

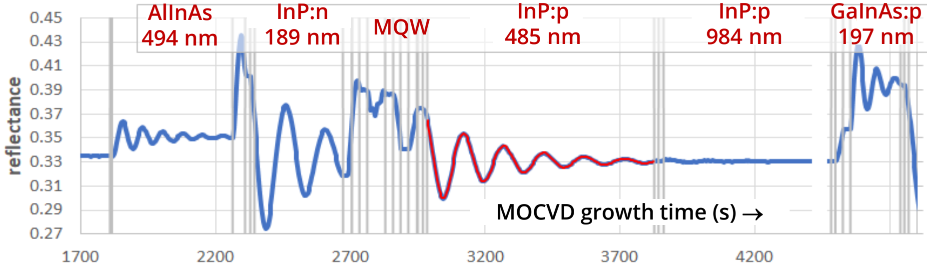




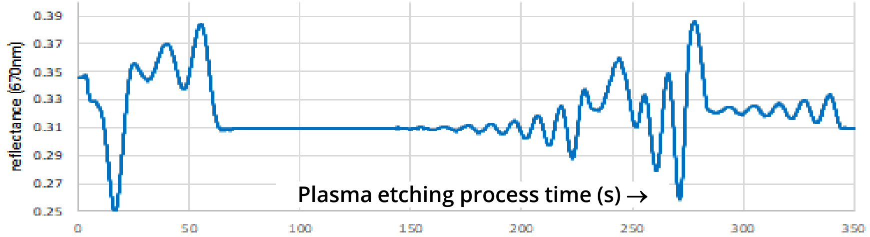
- In-situ metrology during epitaxy
  - Measure growth rate and layer thickness
  - Interface detection by communication with epi tool
  - Thickness information can be used for controlling etching process
- In-situ metrology during etching
  - Interfaces must be detected based on optical signal
  - Etch rate can be measured
  - Residual thickness can be calculated



Reflectance data during growth

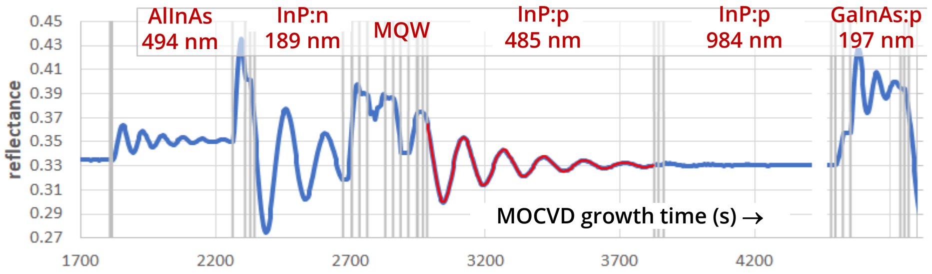


Reflectance data during etching



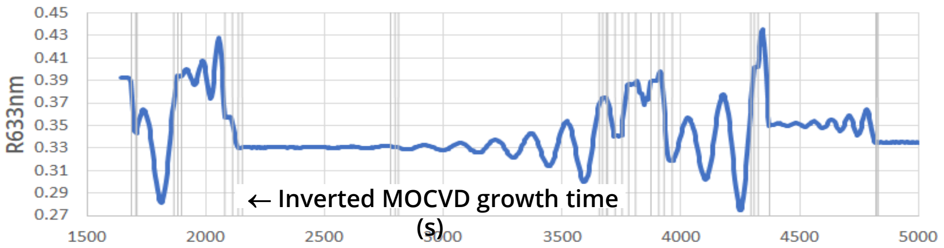
Connection between reflectance data from growth and etching

Reflectance data during growth



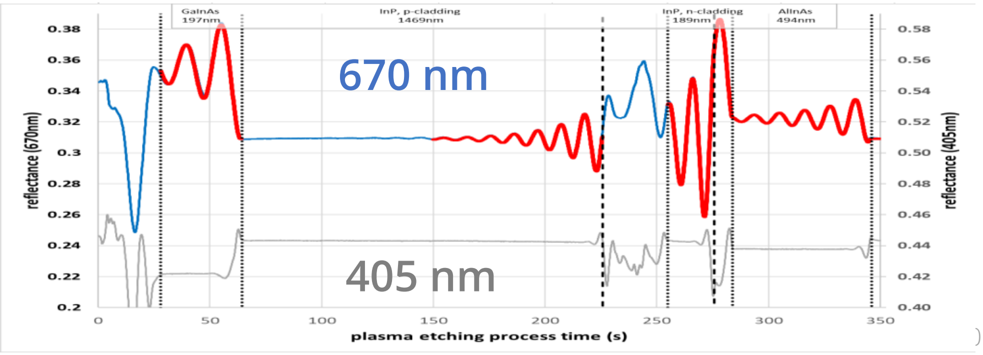
- layer thickness measurements with accuracy in ±1nm range
- Valve actions mark begin/end of layers
- At epitaxy temperatures (~700°C)

Reflectance data during growth – time inverted



- “Preview” to etch measurements

Reflectance data during plasma etching



- Very similar to the epi signal – “etching into a known structure”
- Differences in measurement wavelength, etch rates and temperatures
- Interfaces must be detected in real-time
- Need for a second, shorter measurement wavelength

III-V lab

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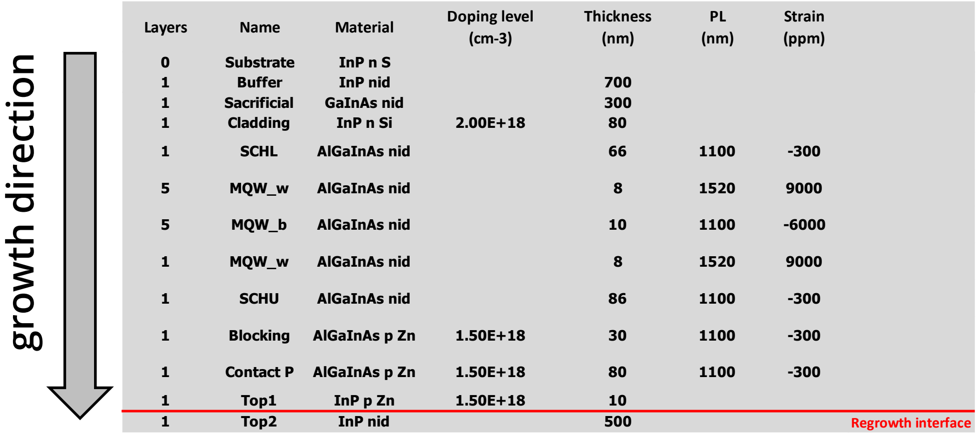
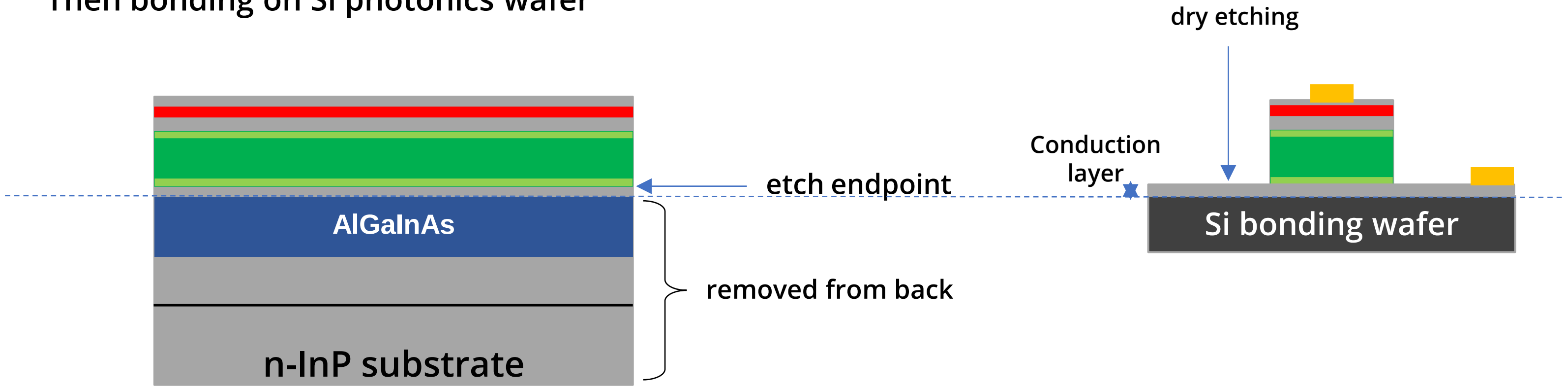
Endpointing specs

- Endpoint detection algorithm for device performance
  - Need to leave very thin layers for electrical conduction after etching
  - avoid etching too deep in conductive regions allowing for lower series resistance
- To be precise, usually CH_4/H_2 based etching is used
  - Issue: it takes hours
  - Switching to Cl_2 based chemistry would save time, but controlling etch depth can be an issue
- Goal
  - Stop etching at the beginning of InP cladding layer
  - Substrate and sacrificial GaInAs layer is later removed from back
  - Then bonding on Si photonics wafer



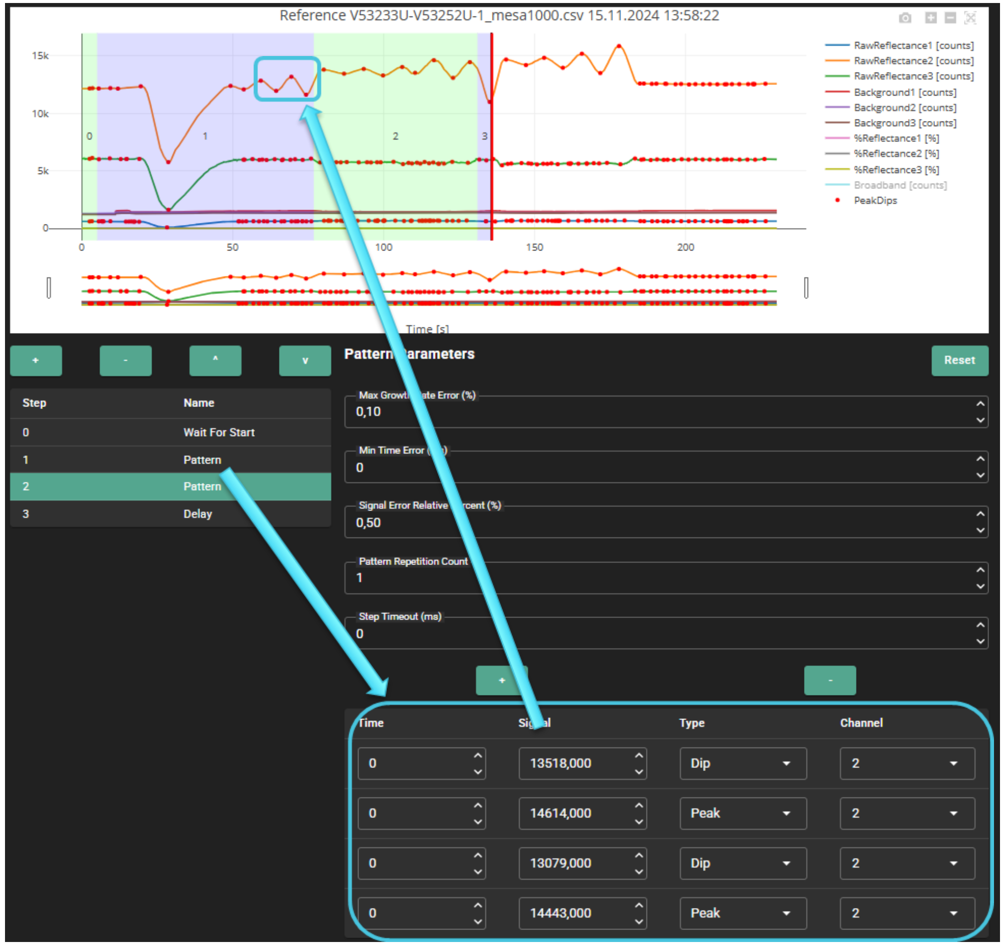
Layers	Name	Material	Doping level (cm-3)	Thickness (nm)	PL (nm)	Strain (ppm)
0	Substrate	InP n S				
1	Buffer	InP nid		700		
1	Sacrificial	GaInAs nid		300		
1	Cladding	InP n Si	2.00E+18	80		
1	SCHL	AlGaInAs nid		66	1100	-300
5	MQW_w	AlGaInAs nid		8	1520	9000
5	MQW_b	AlGaInAs nid		10	1100	-6000
1	MQW_w	AlGaInAs nid		8	1520	9000
1	SCHU	AlGaInAs nid		86	1100	-300
1	Blocking	AlGaInAs p Zn	1.50E+18	30	1100	-300
1	Contact P	AlGaInAs p Zn	1.50E+18	80	1100	-300
1	Top1	InP p Zn	1.50E+18	10		
1	Top2	InP nid		500		

Regrowth interface



Defining endpointing algorithm

- Endpointing algorithm can use all three wavelengths for
  - Interface detection
  - Etch rate measurement
  - Extrema tracking
  - “pattern” recognition
- Algorithm is custom made for each structure, from building blocks in software
- Using “etch through” run as baseline
- When endpoint is detected “stop” signal is transmitted to etching tool (real-time)
- Possible processing delay in etch tool can be accounted for by earlier endpoint conditions
  - Has been observed in the range of 0.5…2s



Step	Name
0	Wait For Start
1	Pattern
2	Pattern
3	Delay

Pattern Parameters

Max Growth Rate Error (%): 0,10

Min Time Error ( ): 0

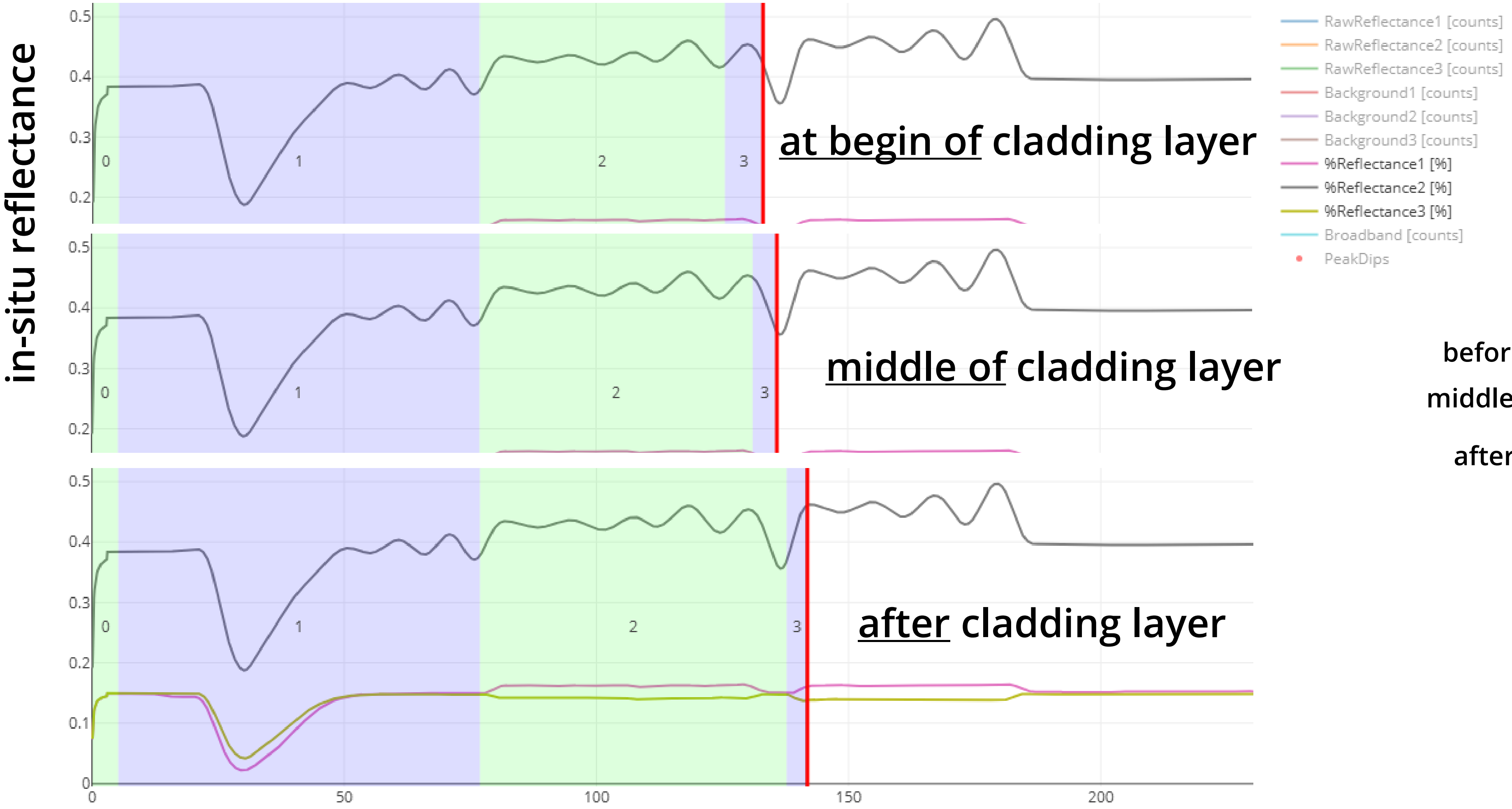
Signal Error Relative Percent (%): 0,50

Pattern Repetition Count: 1

Step Timeout (ms): 0

Time	Signal	Type	Channel
0	13518,000	Dip	2
0	14614,000	Peak	2
0	13079,000	Dip	2
0	14443,000	Peak	2

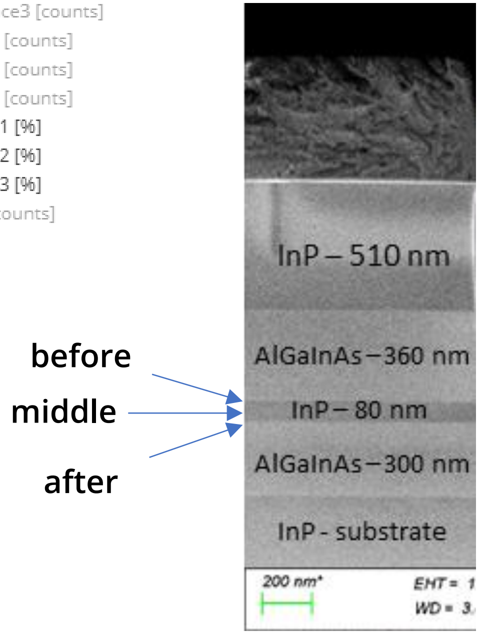
Using and varying endpoint algorithm



at begin of cladding layer

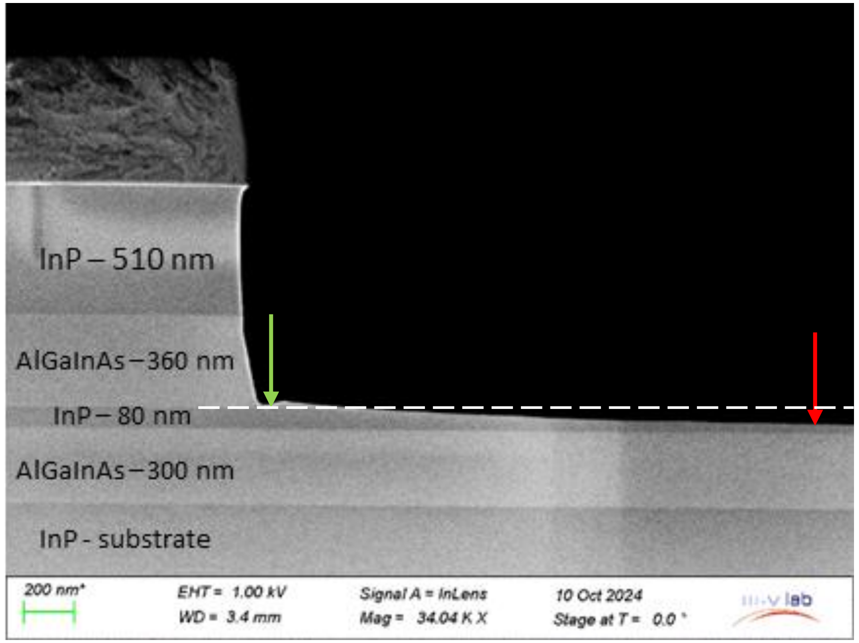
middle of cladding layer

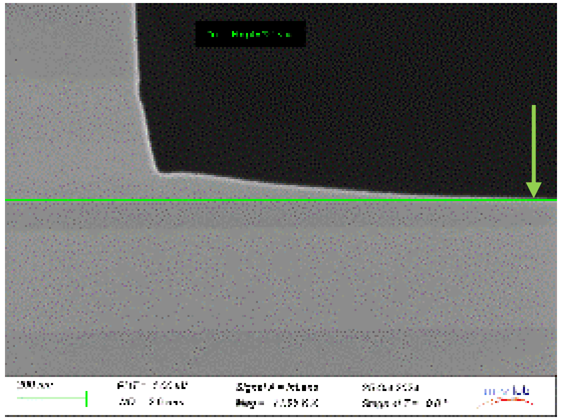
after cladding layer



Validation of correct endpoint

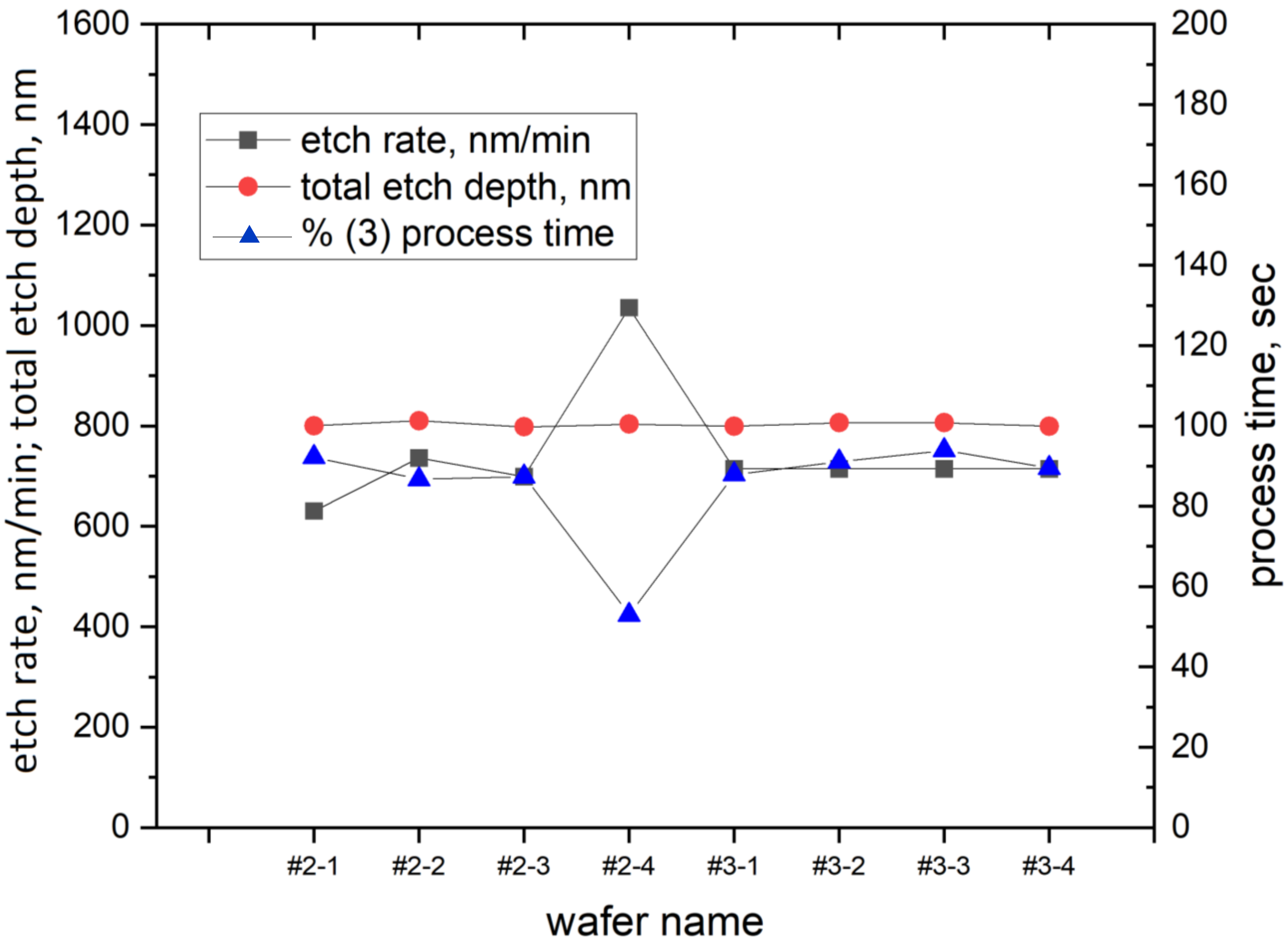
- SEM (scanning electron microscopy) on a patterned sample
  - check stop position with microscopic images of the remaining vertical structure using the mask as reference
- Undesired “foot” is observed
  - etching is non-uniform
- Endpointing is accurate close to mesa (green) – but over etched in open area (red)
- Modified algorithm with slightly earlier endpoint prevents over etching





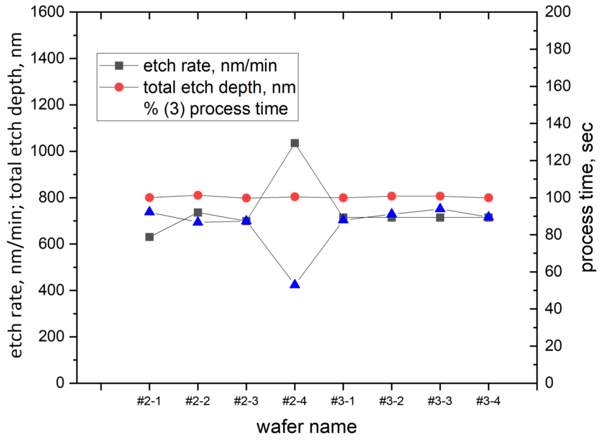
Variation of etch rate

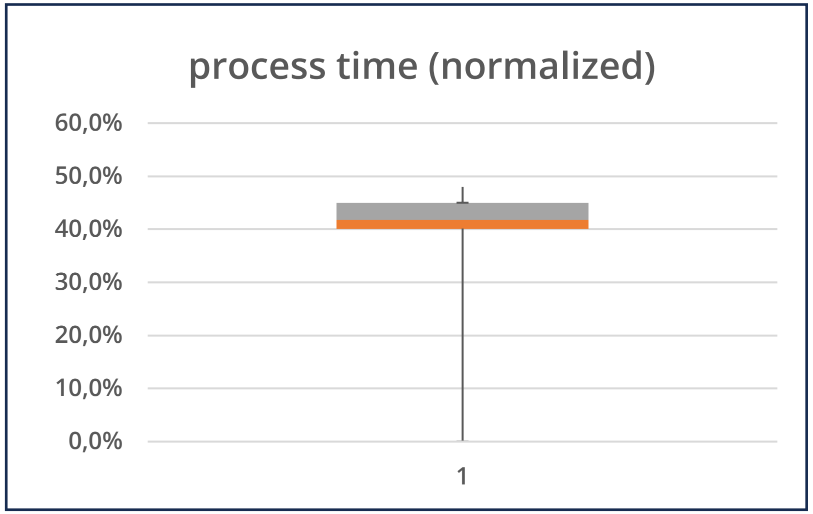
- Variation of etch rate (black)
  - Similar recipe
  - Up top 50% more ICP power
  - +55% in etch rate
- Testing precision (and accuracy) of endpointing
- Etch time (blue) as result of endpointing algorithm
- Etch depth (red) determined ex-situ with profilometer
- Result: Constant etch depth despite huge etch rate variation

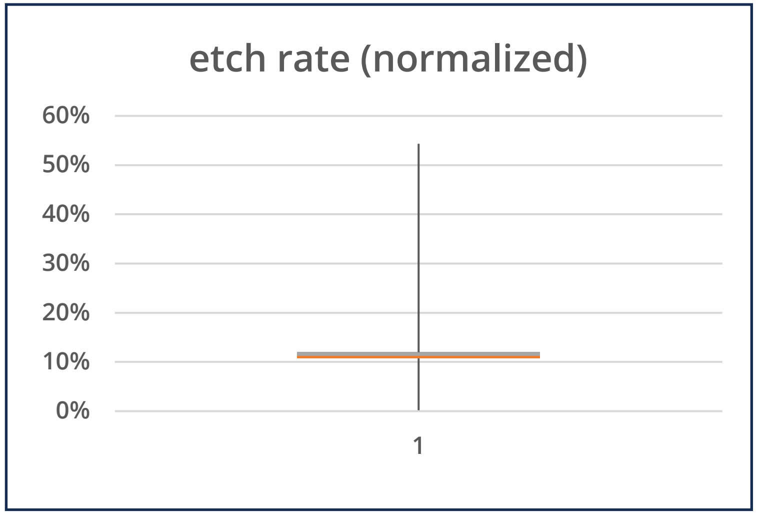


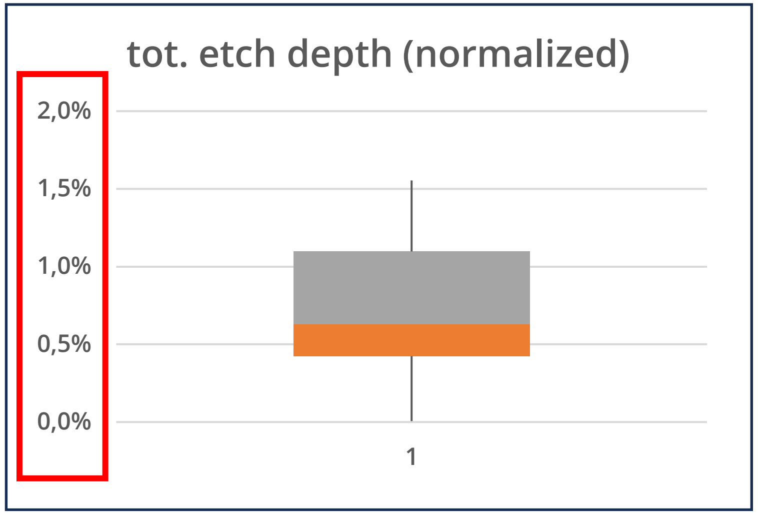
Statistical evaluation

- Box plots for 8 runs show variation of
  - Etch rate
  - Process time
  - Etch depth









→ very reproducible and robust endpointing procedure

Outline

- Introduction
- Compound Semiconductor manufacturing chain and optical metrology
- Experimental for InP laser structures
- Plasma etching and endpointing
- Summary & Outlook

Summary

- Manufacturing of optical device structures with high yield requires metrology at various points of the process chain

- in-situ metrology during epitaxy (MOCVD) is state-of-the-art
  - Reflectometry can be used to determine growth rate and layer thickness in real-time using thin film interference
  - Time-inverted reflectance measurement provides preview of plasma etching process

- In-situ metrology during plasma etching
  - Reflectance based in-situ metrology allows precise endpointing before, in the middle of after a certain layer
  - Reliable endpointing even w/o etch stop layers, enables shorter process times (reducing Cost of Ownership)
  - Sub-nm precision can be reached and is confirmed by x-section SEM
  - Endpointing method is insensitive to variations of etch rate
  - Communication delay in Plasma Etching tool can be compensated
  - Prior knowledge of epi thickness is useful for defining endpointing algorithm
  - Method works universal for any compound material and device type

- "Connected Metrology" provides additional benefits: Using up-stream metrology data for controlling down-stream processes

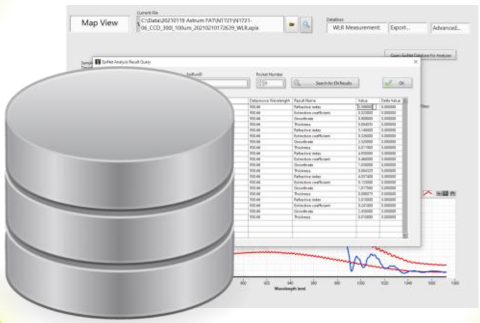
LayTec “Metrology Ecosystem”

Connected Metrology

***EpiCurveTT*:**
in-situ measured layer thickness
and other layer properties

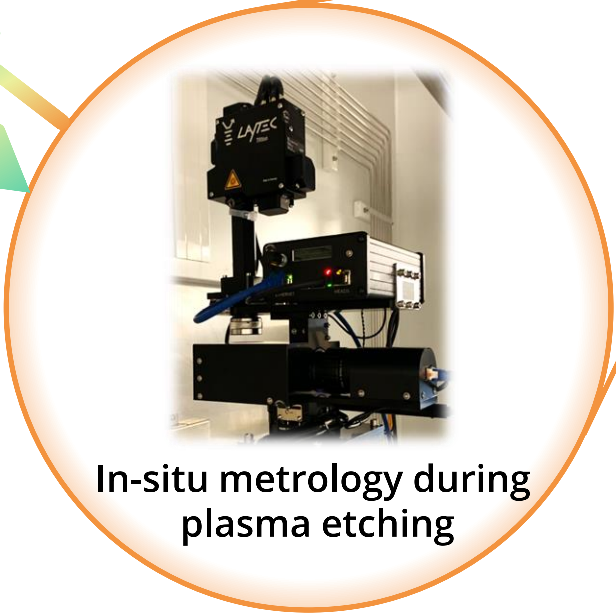
In-situ metrology
during MOCVD

Database of
measured data



Wafer mapping

EpiX:
spatial variation
of layer properties



In-situ metrology during
plasma etching

***Etchpoint* and *TRIton*:**
end point detection based
on actual layer thickness

- The same wafer is measured 3+ times
- The amount of information increases
- and is combined for improved analysis in downstream processes

Knowledge is key

www.laytec.de

III-V lab

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