In-situ and in-line metrology in front end production of ultra-high-yield diode lasers

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25 YEARS

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Outline

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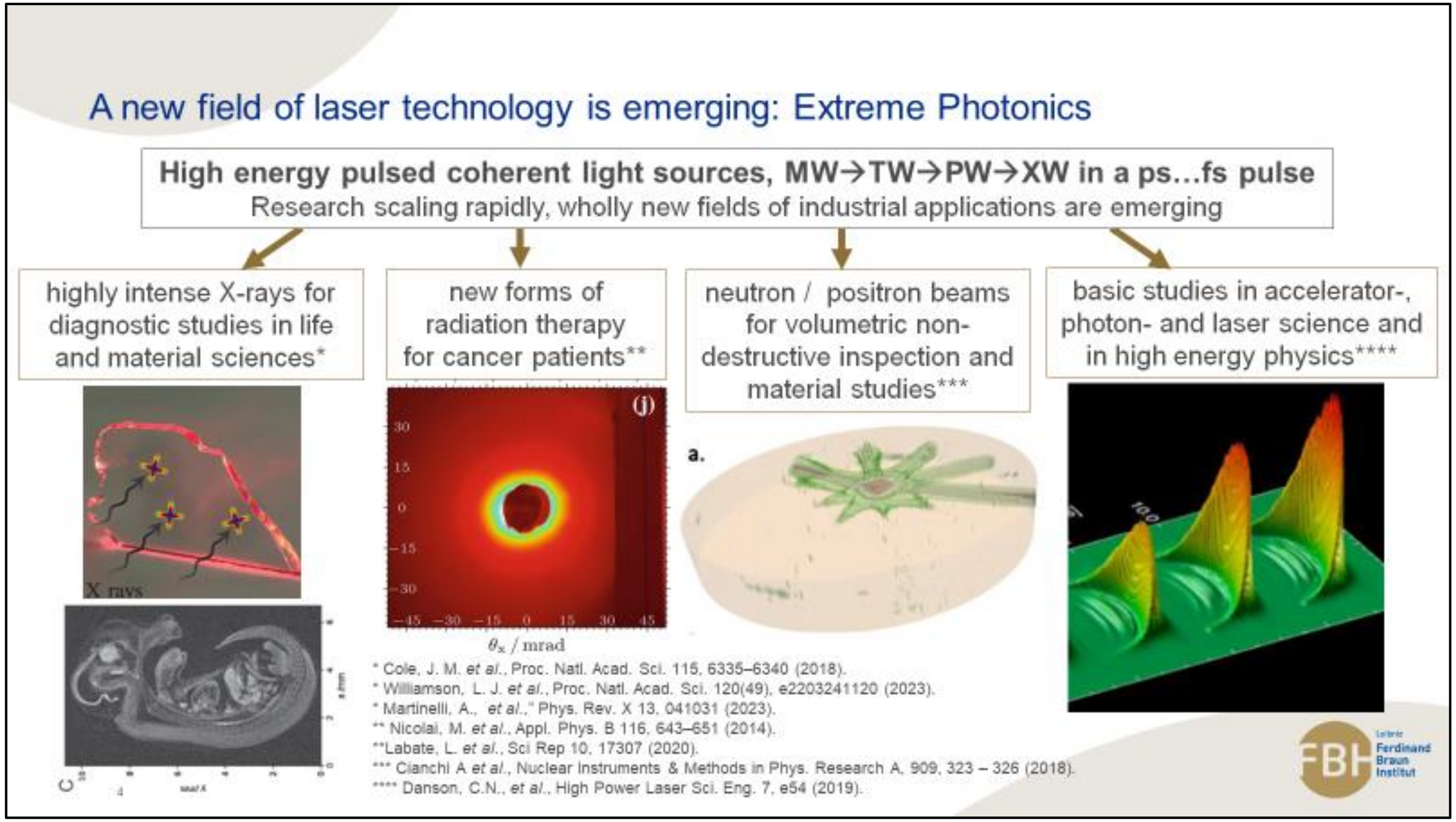
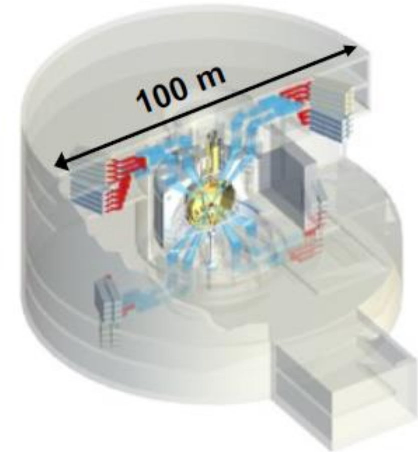
Outline

Extreme Photonics is emerging, needs extremely large numbers of diode lasers



Not to forget fusion, the largest application in extreme photonics…

IFE plant: >10 Hz



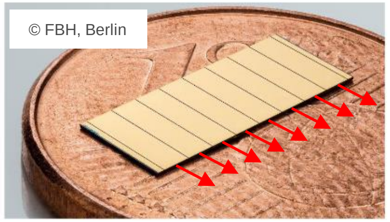
See for example: Prof. Dr. Constantin Haefner
"**The German Roadmap on IFE state of the art and prospective**"
Managing Director Fraunhofer ILT
Lead BMBF Expert Commission Inertial Fusion Energy
Commissioner for Fusion Research of the Fraunhofer-Gesellschaft
Laser induced fusion: kick off meeting, ELI Prague, Czech Republic, November 28-29, 2023

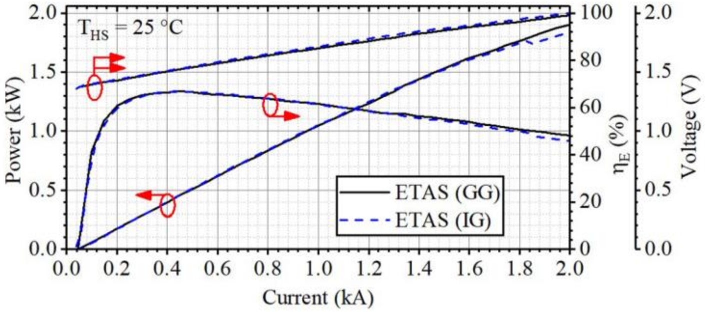
Slides from: P. Crump and L.A. Gizzi "Diode pumps for future laser plasma accelerators: perspectives from research and industry" Proc. SPIE 12867, 128670R (2024)

Diode Laser Bars in large volumes as enabler for fusion: very high yield needed

Diode Laser Arrays (bars)

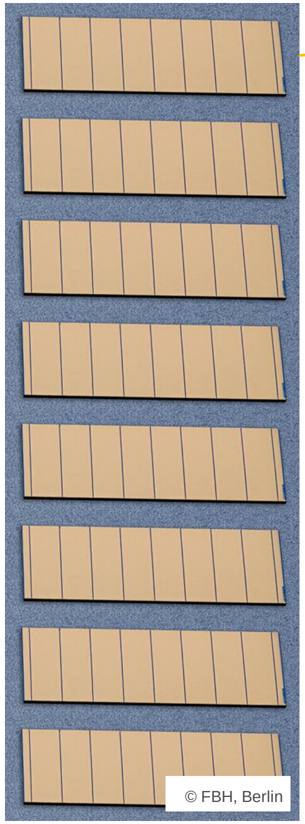
1000 W output power, > 60% efficiency
1 cm aperture, 4 mm resonator



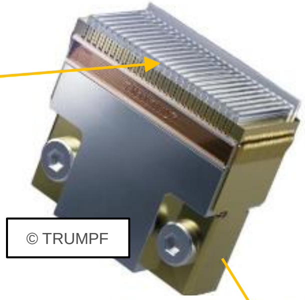


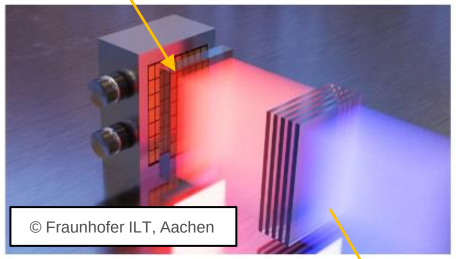
Md. J. Miah *et al.* IEEE PJ 14(3), 1525505 (2022)

Fabricated in large numbers



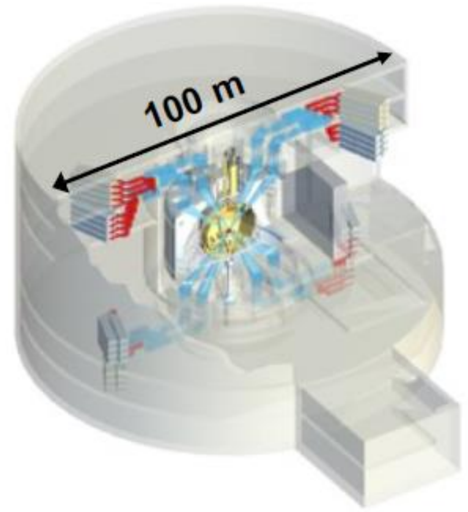
Assembled into laser drivers





Integrated in fusion power plant

IFE plant: >10 Hz



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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

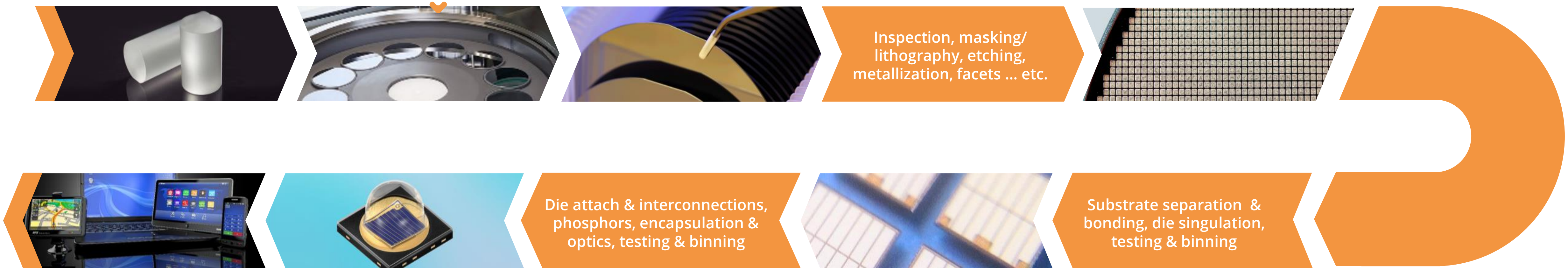
Substrate

Front-end
Level 0 - Epitaxy

Epi-wafer

Front-end
Level 1 – Device Production

Dies-on-wafer



systems & applications

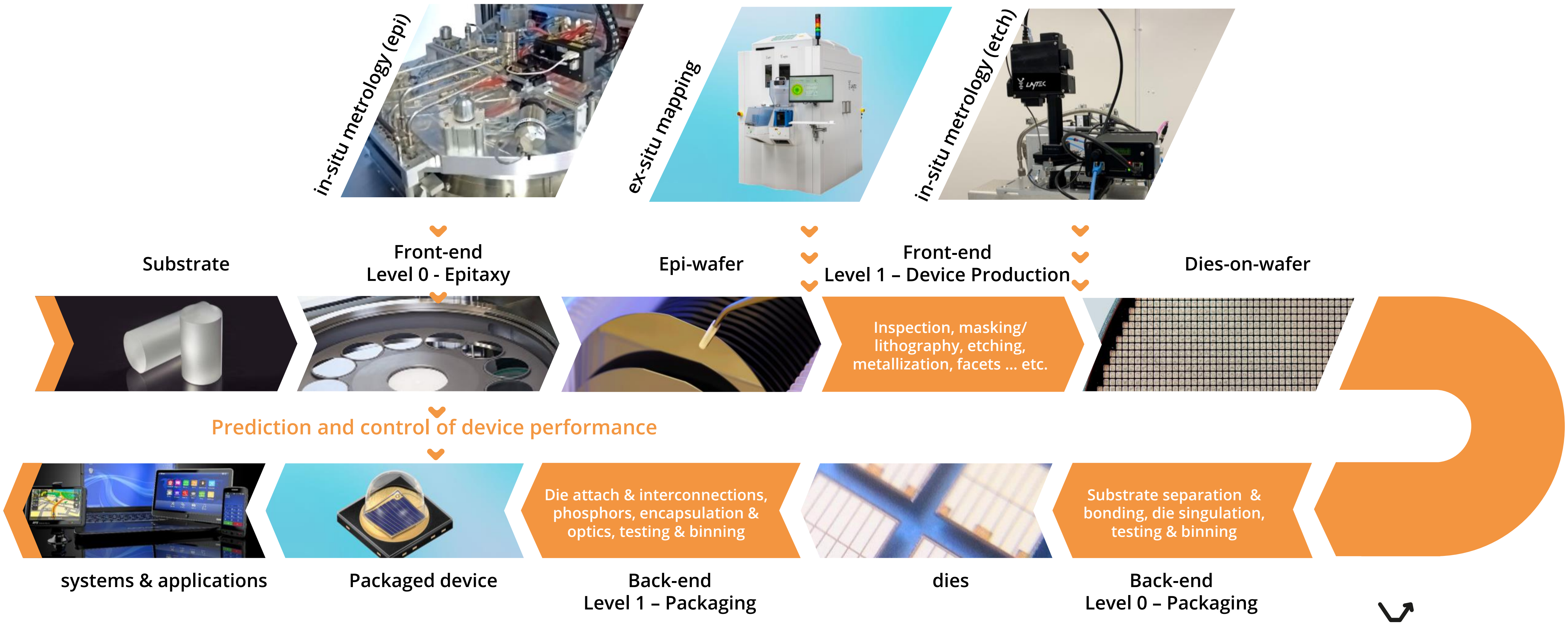
Packaged device

Back-end
Level 1 – Packaging

dies

Back-end
Level 0 – Packaging

Optical metrology along the semiconductor manufacturing chain



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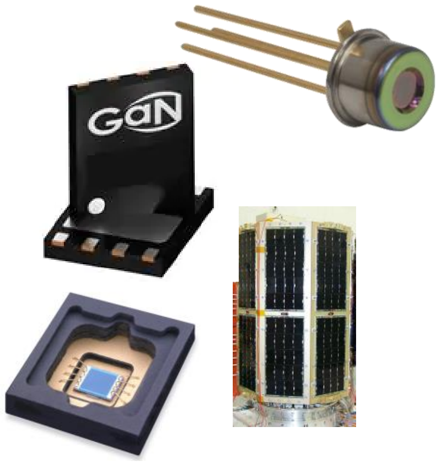
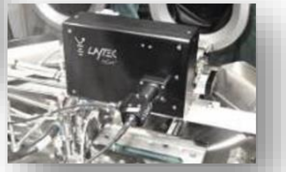
On the road to higher performance, higher yield and lower cost …

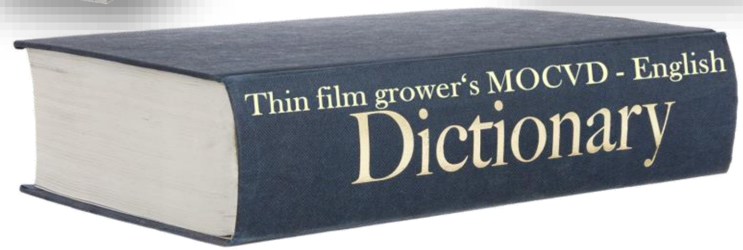


System → Device → Material → Process → Production tool

Requirements →

← Understanding





→ Metrology helps you to understand – metrology can be your dictionary!

Outline

- Motivation
- Experimental
- MOCVD growth
- Wafer mapping
- Plasma etching
- Summary

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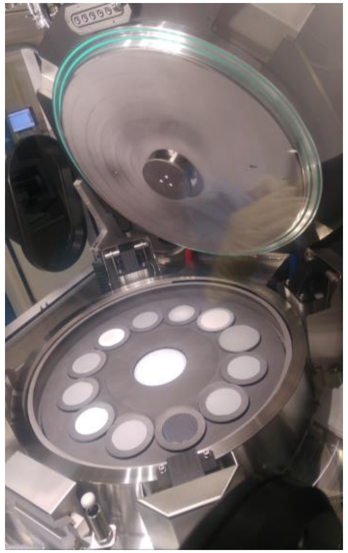
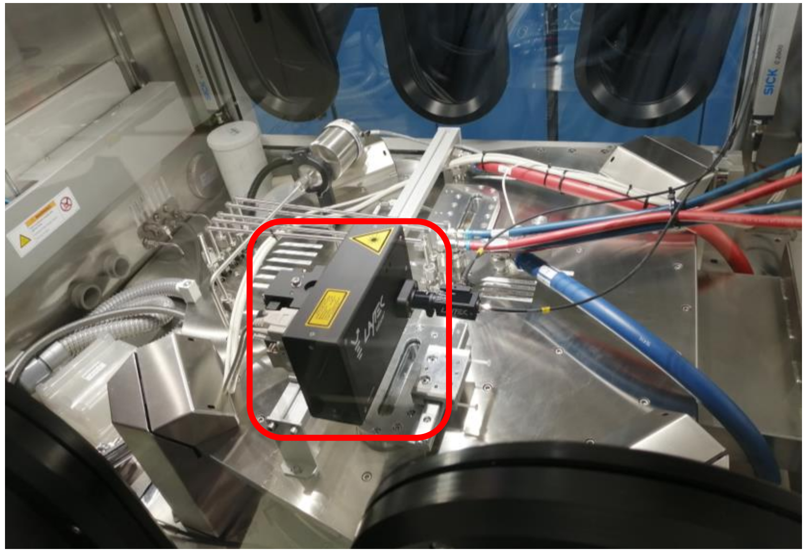
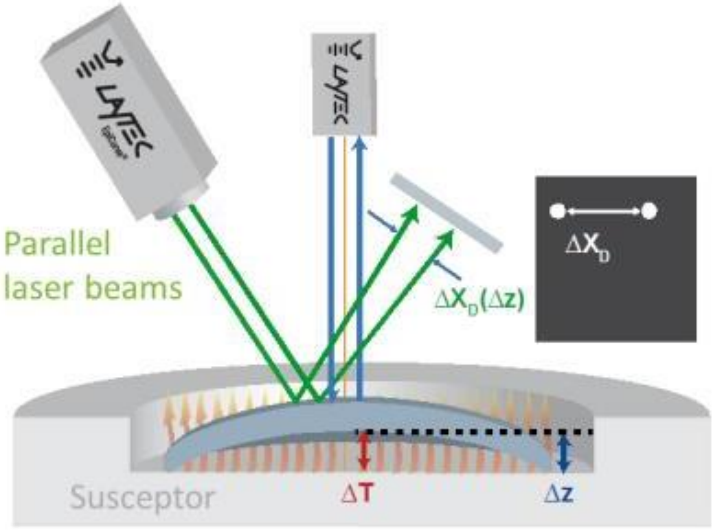
MOVPE growth of GaAs-based laser diodes



AIX 2800 G4 planetary reactor
12x4” or 12x3” configuration



EpiCurve® TT AR spectral in-situ metrology
(measurement head is installed on the reactor lid)



Schematical metrology setup

- Group V precursors: AsH_3, PH_3 / Group III precursors: TMAl, TMGa, TMIn
- Typical n-dopants: Si_2H_6 / Typical p-dopants: DMZn, CBr_4
- In-situ measurement of **wafer temperature**, multi-wavelength **reflectance** and **wafer curvature**
- Control of temperature, monitoring of growth rate/layer thickness and composition
- Individual measurement of each wafer

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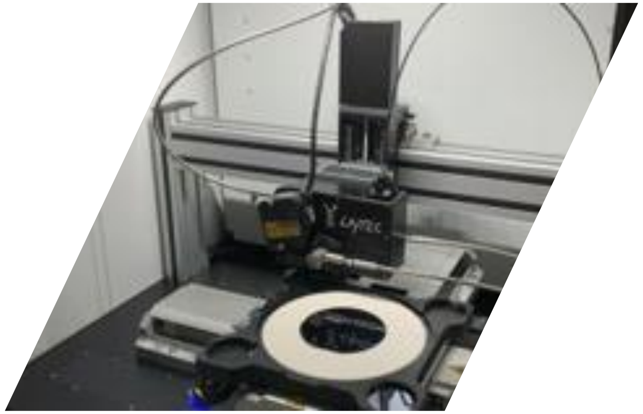
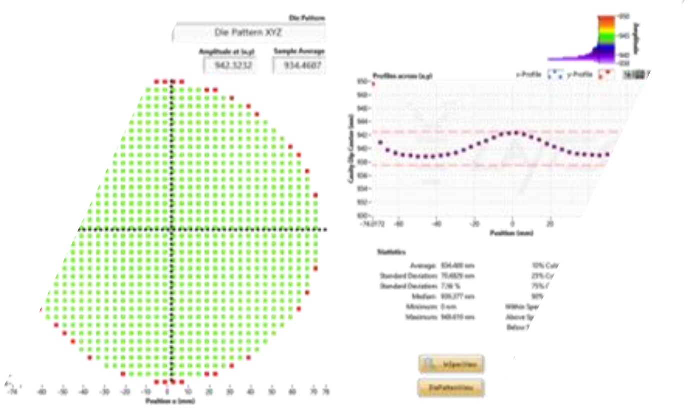
Post-epi wafer mapping

LayTec EpiX
wafer mapper





- Mapping of **white light reflectance** in UV/vis/NIR and **photoluminescence**
- Typical pitch 0.1mm
- Analysis of layer thickness and uniformity
- Benefit from mapping
  - in-situ linescan only in one direction possible (azimuthal)
  - No radial information available due to viewport positions
  - Mapping shows defects in substrate or layer
  - Mapping provides missing information (uniformity flat/anti-flat direction)
  - data can be used to tune heating zones

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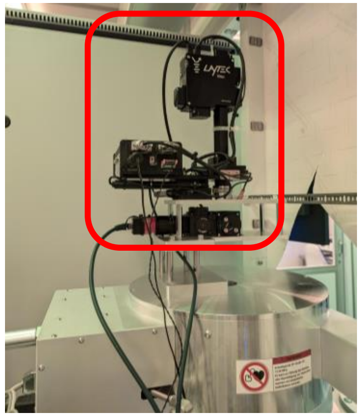
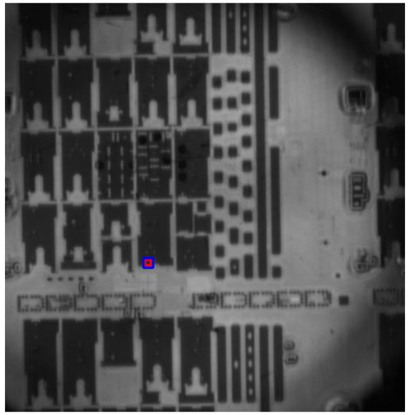
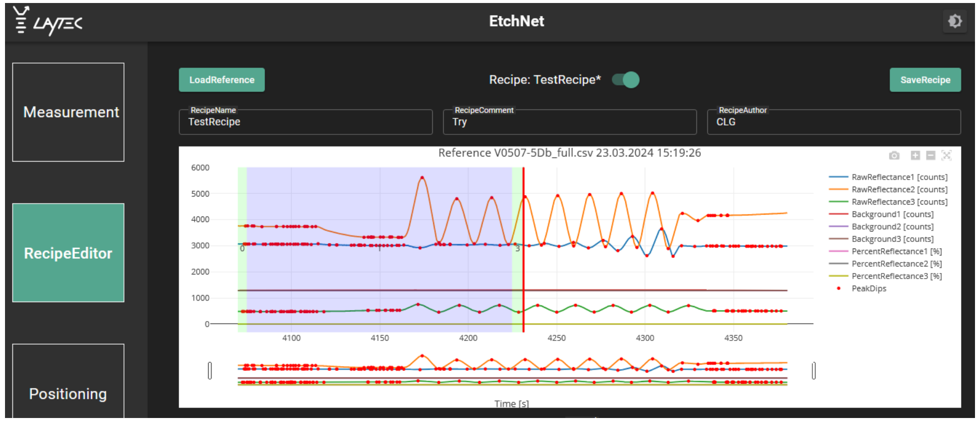
In-situ metrology during plasma etching



Multi-wavelength in-situ metrology TRIton on ICP (SENTECH Instruments SI500)



measurement spot
on a patterned wafer



Real-time view during etching

- Plasma etching (RIE/ICP) is used to etch back into the wafer, e.g. to define contacts
- Precise and reliable stopping the etching process („endpointing“) is crucial for the yield
- Reflectance based **interferometry** tool
- Three wavelengths vis/UV
- CCD camera for pattern recognition with 10µm resolution
- Motorized stage for automated positioning
- Automated end-pointing algorithms

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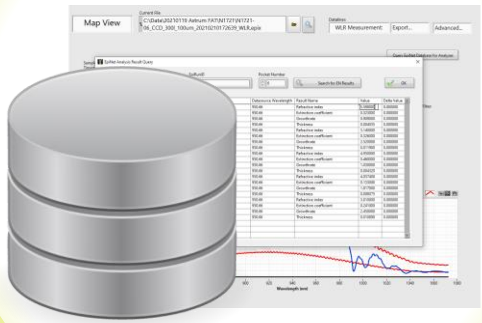
LayTec "Metrology Ecosystem"

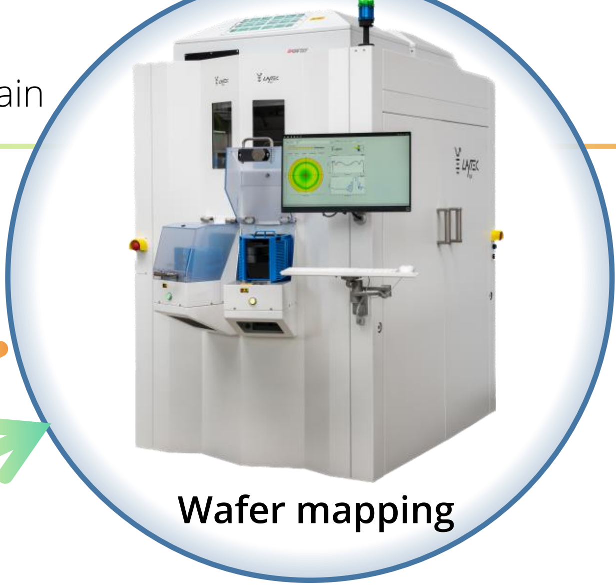
Connected Metrology

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

In-situ metrology
during MOCVD

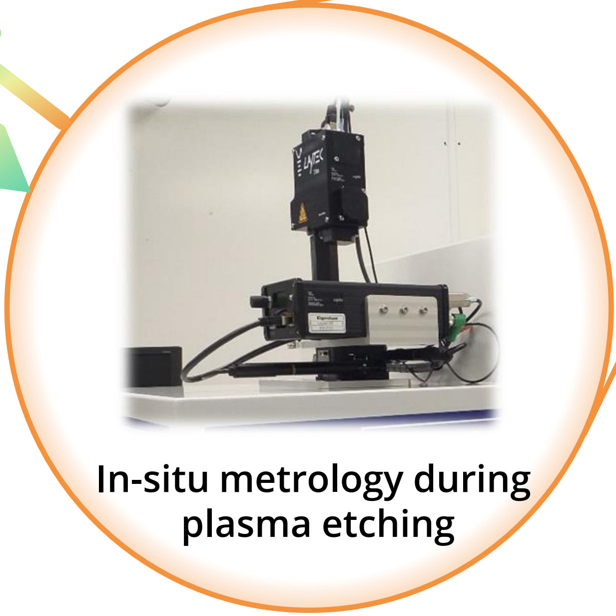
Database of
measured data





Wafer mapping

***EpiX*:**
spatial variation
of layer properties



In-situ metrology during
plasma etching

***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

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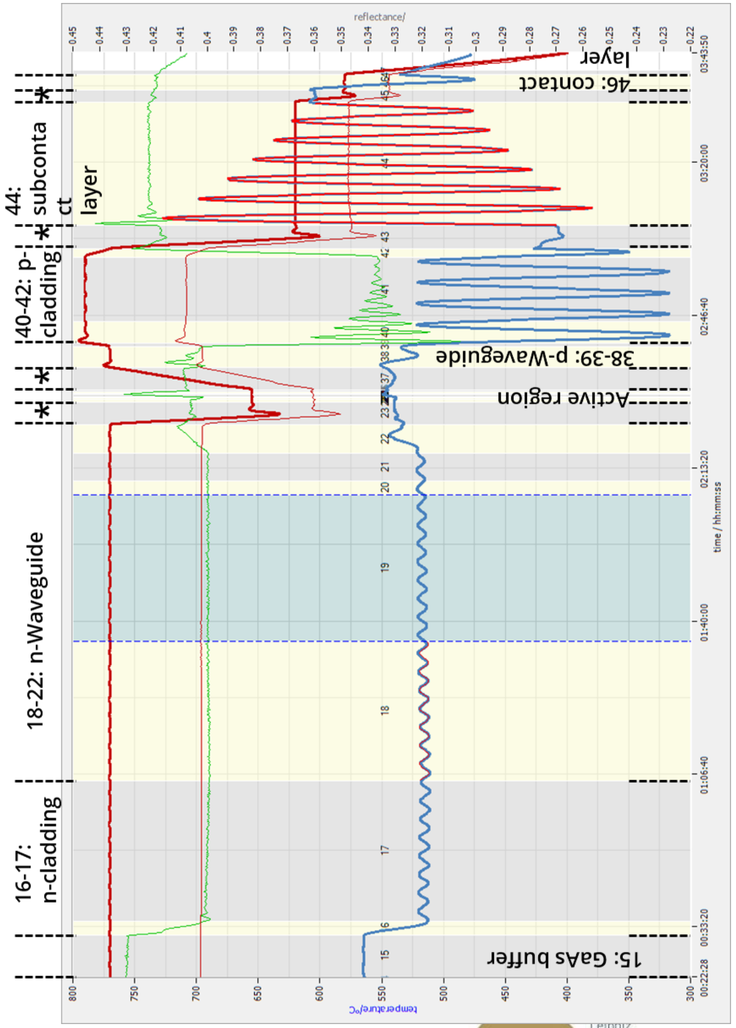
In-situ metrology data from MOVPE of AlGaAs/GaAs laser structures

Schematic layer stack of laser

Contact layer	p-GaAs
Cladding layer	p-AlGaAs GRIN
Waveguide Layer (WL)	p-AlGaAs
Spacer	GaAsP
Active region	InGaAs
Spacer	GaAsP
Waveguide Layer (WL)	n-AlGaAs
Cladding layer	n-AlGaAs GRIN
Buffer	n-GaAs
Substrate	GaAs

Growth time



In-situ data

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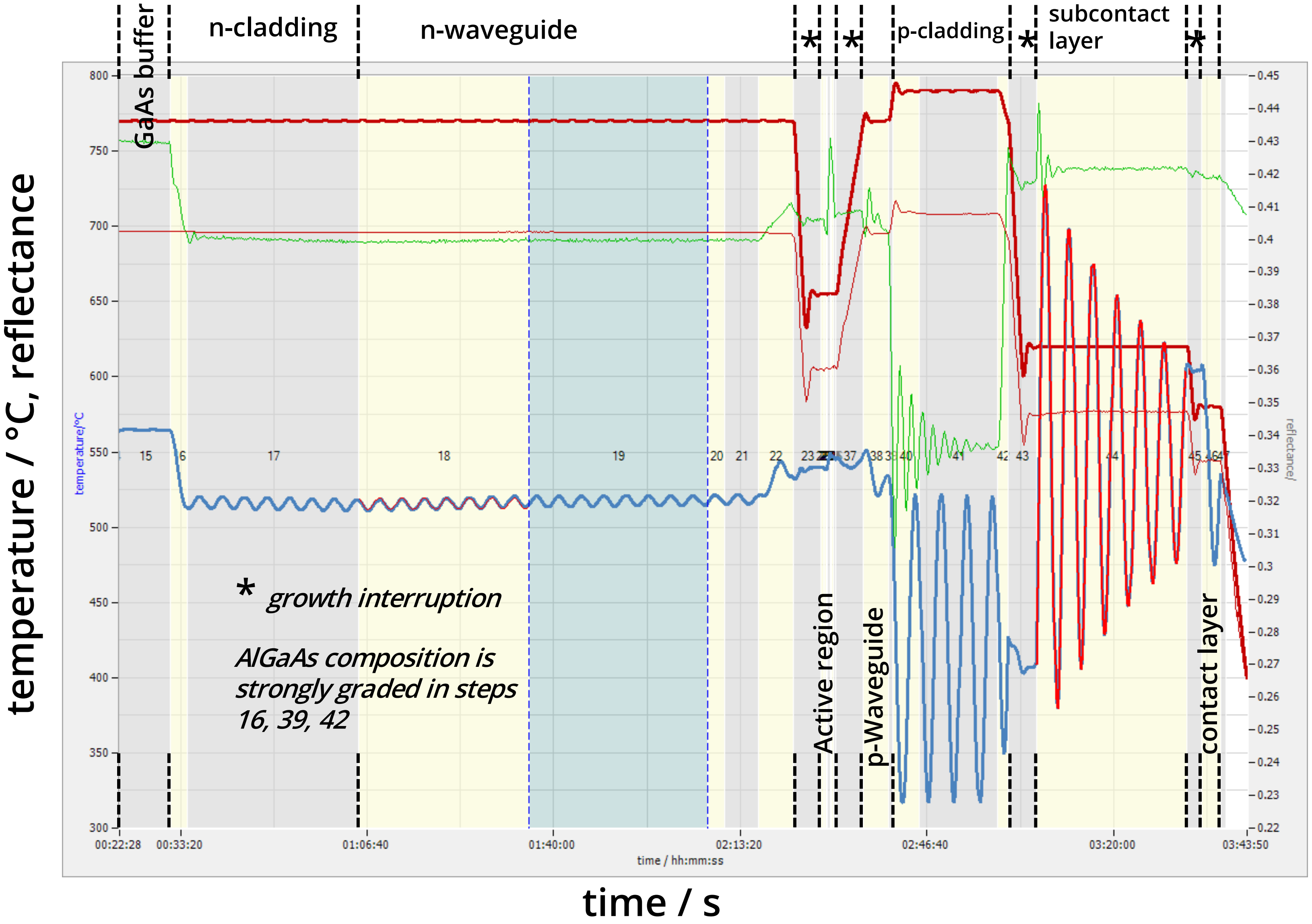
In-situ metrology data from MOVPE of AlGaAs/GaAs laser structures

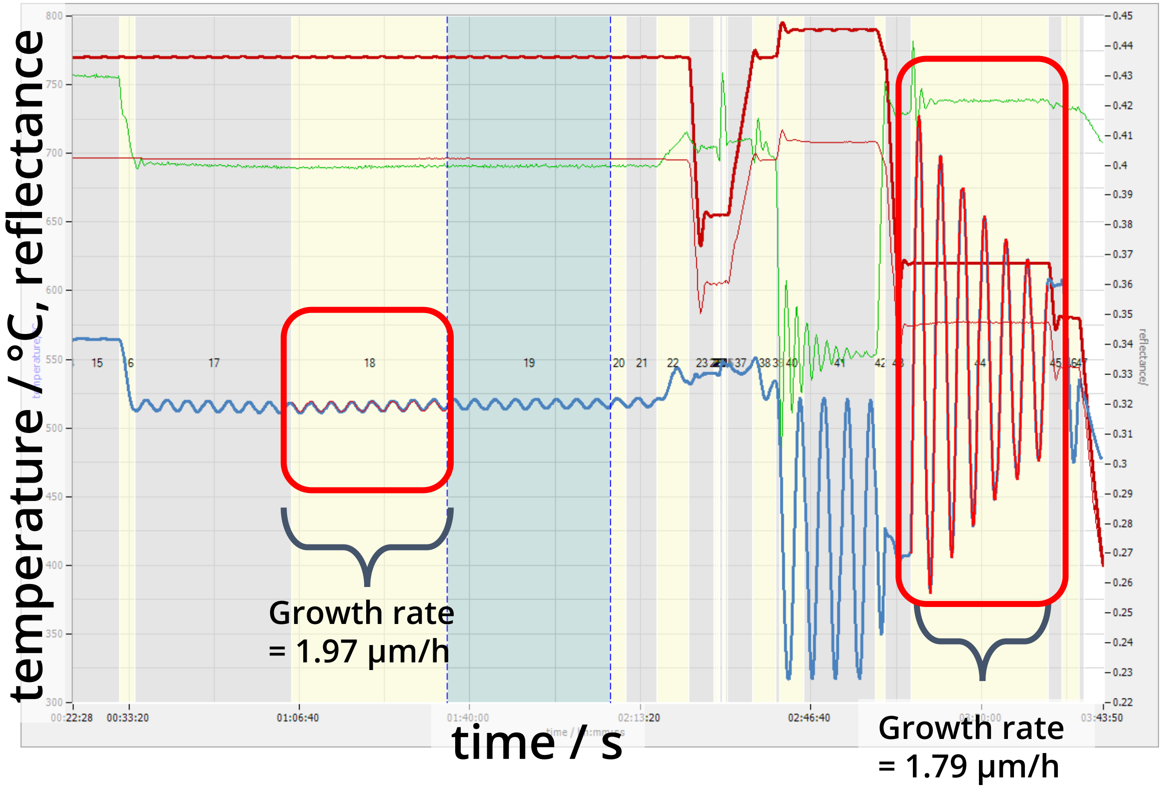


Pocket temperature
Wafer temperature

Reflectance 489nm
Reflectance 948nm
(Reflectance 633nm)

- All layers are identified
- Quantitative analysis of growth rate/layer thickness and ternary composition
- In-situ data:
  A treasure trove of information about each layer and each wafer

In-situ metrology data from MOVPE of AlGaAs/GaAs laser structures



- Analysis of AlGaAs layers provides the growth rate/layer thickness
- Changes in of reflectivity of short wavelength signal indicate development of surface roughness
- Wafer curvature is used to assess indium incorporation in AlInAs and AlGaInP

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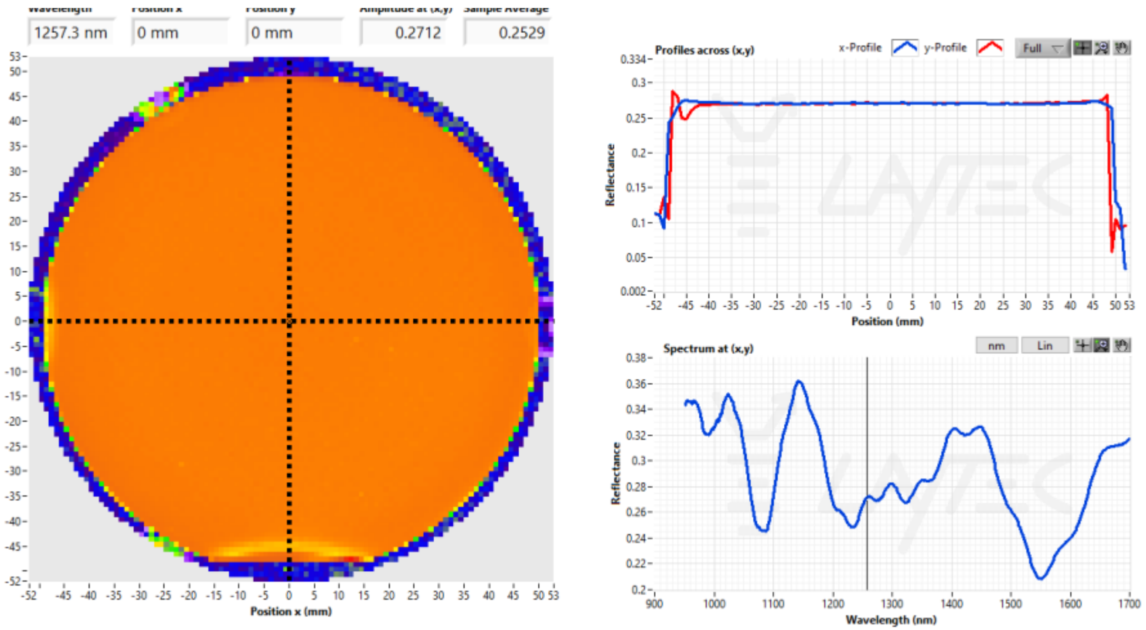
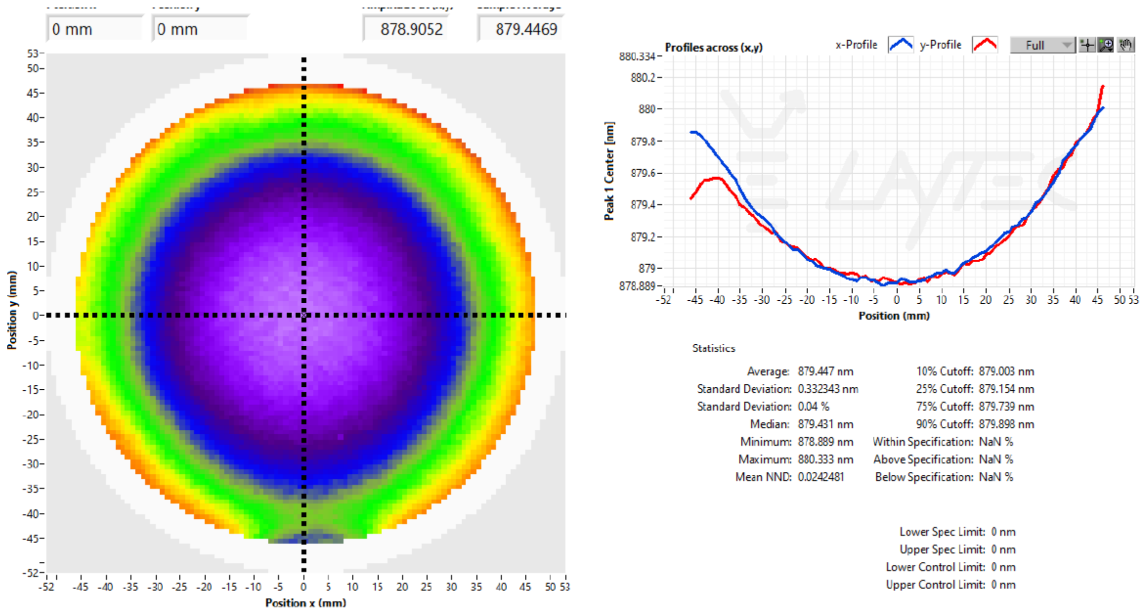
Results of post-epi wafer mapping



White light reflectance (vis/NIR)



Photoluminescence map (laser 785nm)

- Determination of uniformity of MOVPE growth; analysis together with in-situ data from epi
- Features from wafer supports in MOVPE process visible
- PL less uniform than reflectance

Outline

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Plasma etching – „inverted“ growth

Reflectance - as measured during epi

reflectance

time / s

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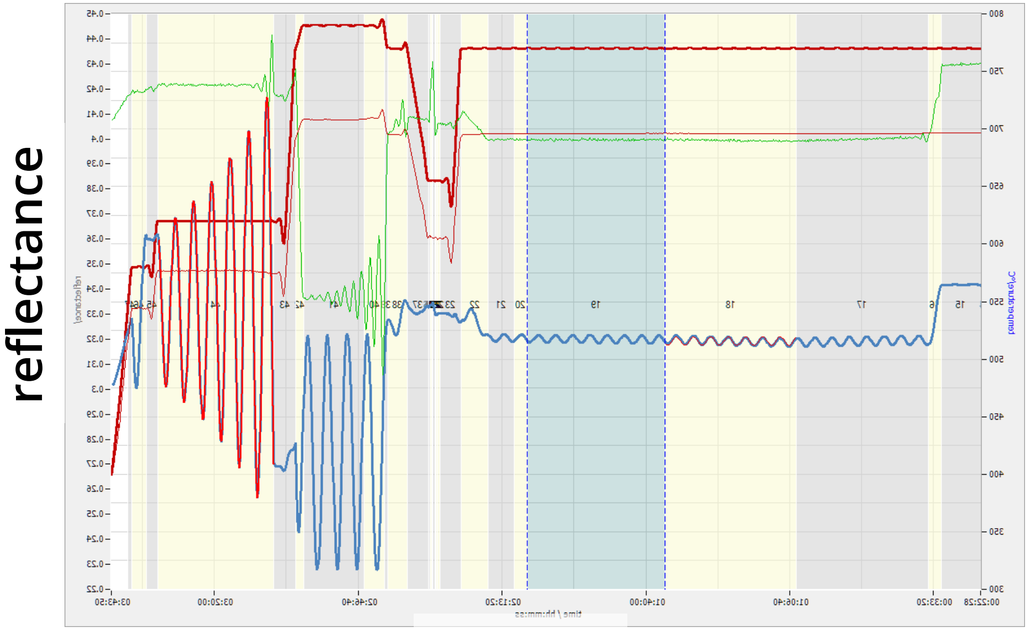
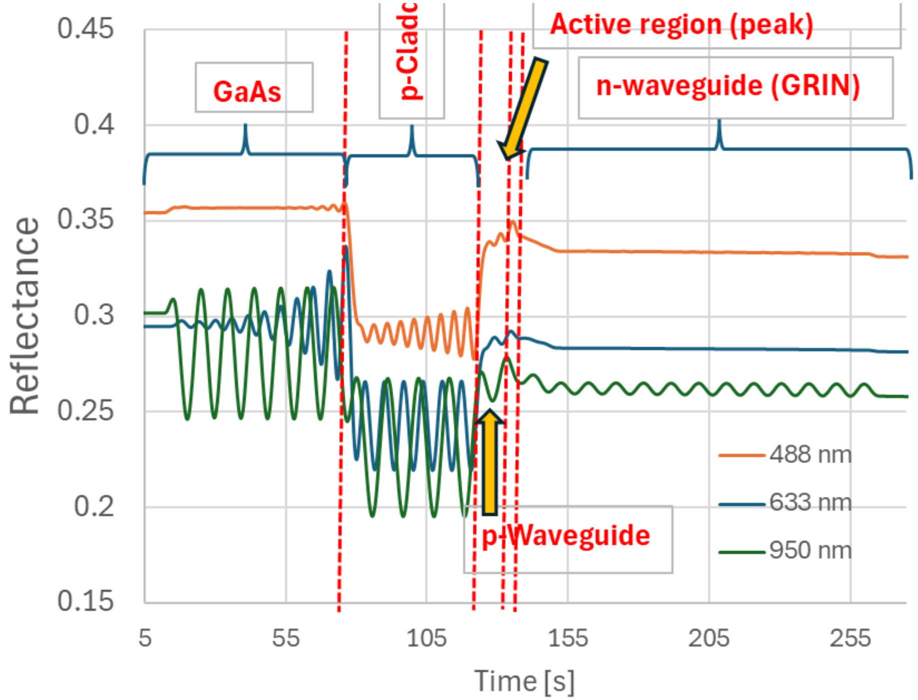
Plasma etching – „inverted“ growth

Reflectance - time inverted



Reflectance – as measured during etch



- Reflectance measurement during epi can be used as „target“ for etch process
- By taking advantage of the wafer ID, you are etching into a known structure
- „enpointing“ is strongly facilitated by using „upstream“ data

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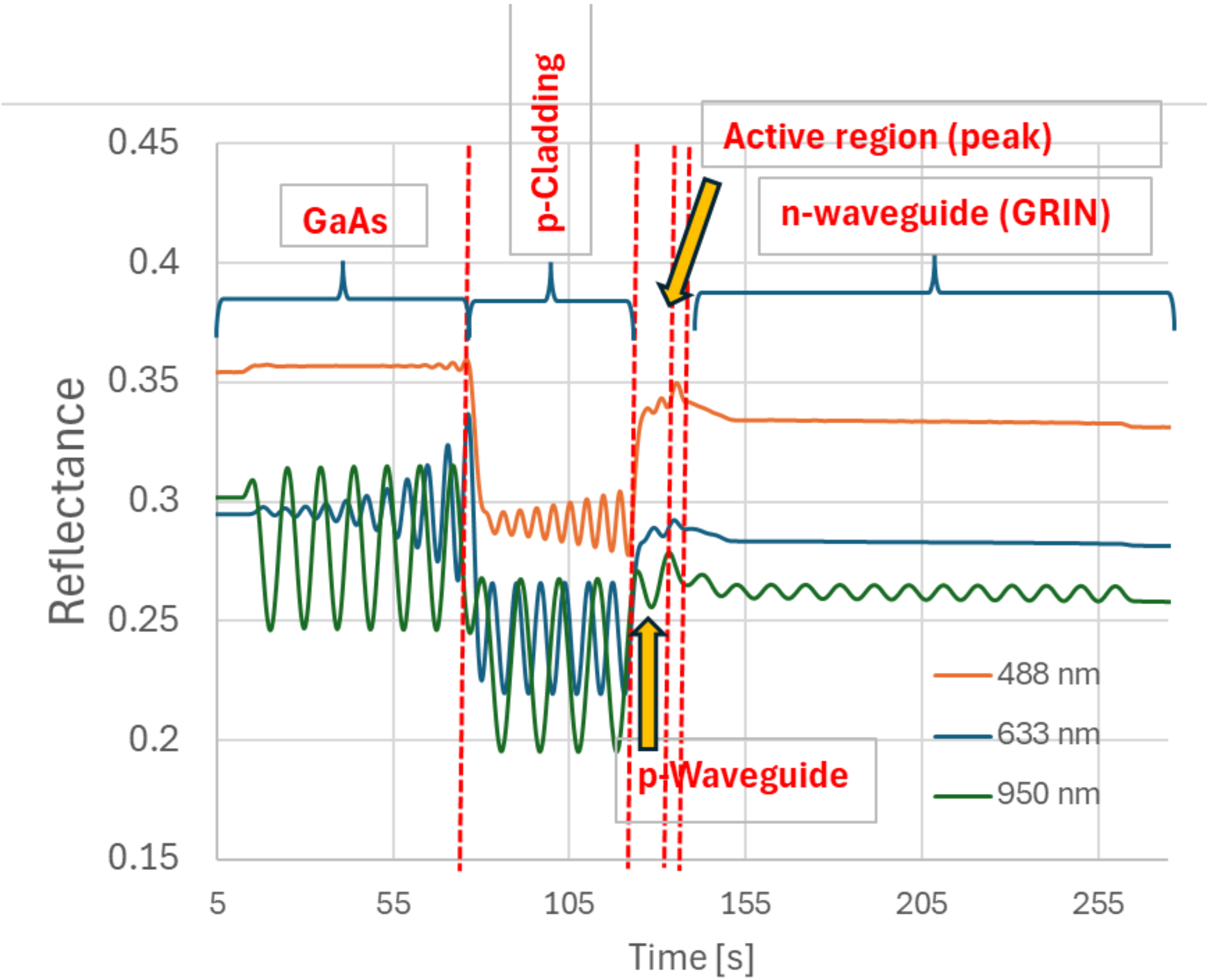
In-situ metrology during plasma etching for end pointing

- three wavelength based in-situ metrology for dry etch enables
  - Measurement of the etch depth and etch rate in different layers
  - Detection of interfaces with nm-accuracy
- Endpoint detection requirement
  - in n-waveguide with high accuracy
  - w/o etch stop layer
- robust endpointing even in case of noticable wafer-to-wafer variations



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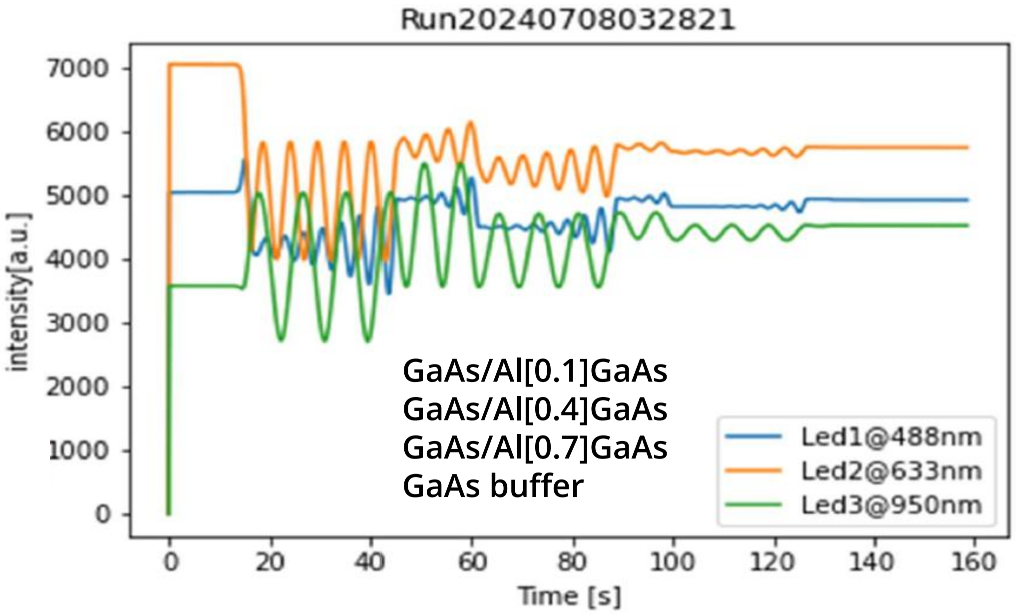
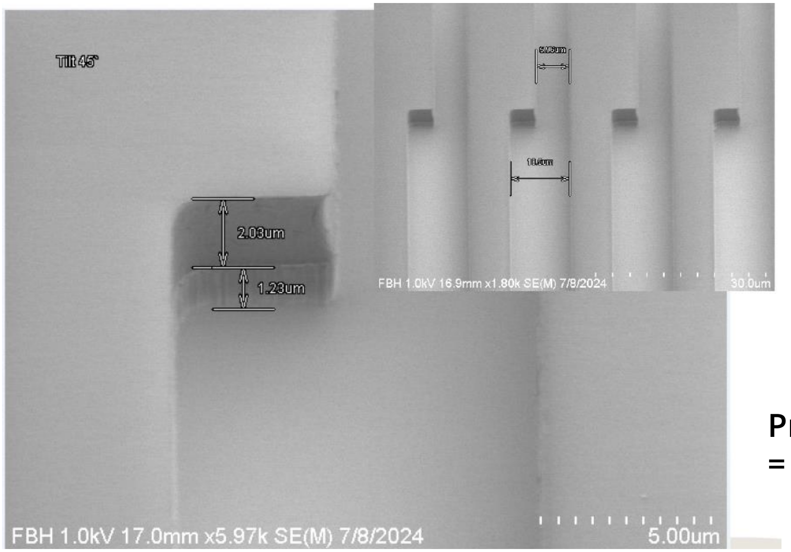
Benchmarking the accuracy for endpointing

- Growing non-confidential AlGaAs/GaAs test structure
- Etching ~2.5µm deep
- Comparing in-situ measured etch rate with Scanning Electron Microscope



Etch Rate = 1.08 µm/min



Profiler: Etch Rate = 1.08 µm/min

- **Measurement accuracy better than 1%**

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Outline

Summary

- Manufacturing high power lasers with high yield requires metrology at various points of the process chain

- Use of integrated in-situ metrology during MOCVD is state-of-the-art
  - Control of wafer temperature, growth rate and ternary composition is crucial
  - Allows to catch defects or errors in the growth, much quicker than waiting for final test results
  - Tracking and compensating for changes in reactor conditions (e.g. material deposition on the walls)
  - Quick “reactor calibration” using test structures (GaAs/AlGaAs layer stacks at different growth temperatures)
  - Possible to grow structures in “uncharted” territory or to re-establish growth conditions after maintenance

- Post epi Wafer Mapping
  - Analysis of uniformity of epi growth and photoluminescence
  - Valuable for tuning of heating zones
  - Combined analysis of mapping results with in-situ measured layer thicknesses
  - Compensating thickness variations for test pads during plasma etching

- In-situ metrology during plasma etching
  - Reliable “endpointing” w/o etch stop layers
  - Prior knowledge of epi thickness is useful for defining etch depths

- “Connected Metrology” provides additional value: Using up-stream metrology data for controlling down-stream processes

Knowledge is key

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