Metrology for MOCVD of VCSELs – latest progress for enabling high-yield manufacturing

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LayTec AG

Knowledge is key

European Photonics Industry Consortium

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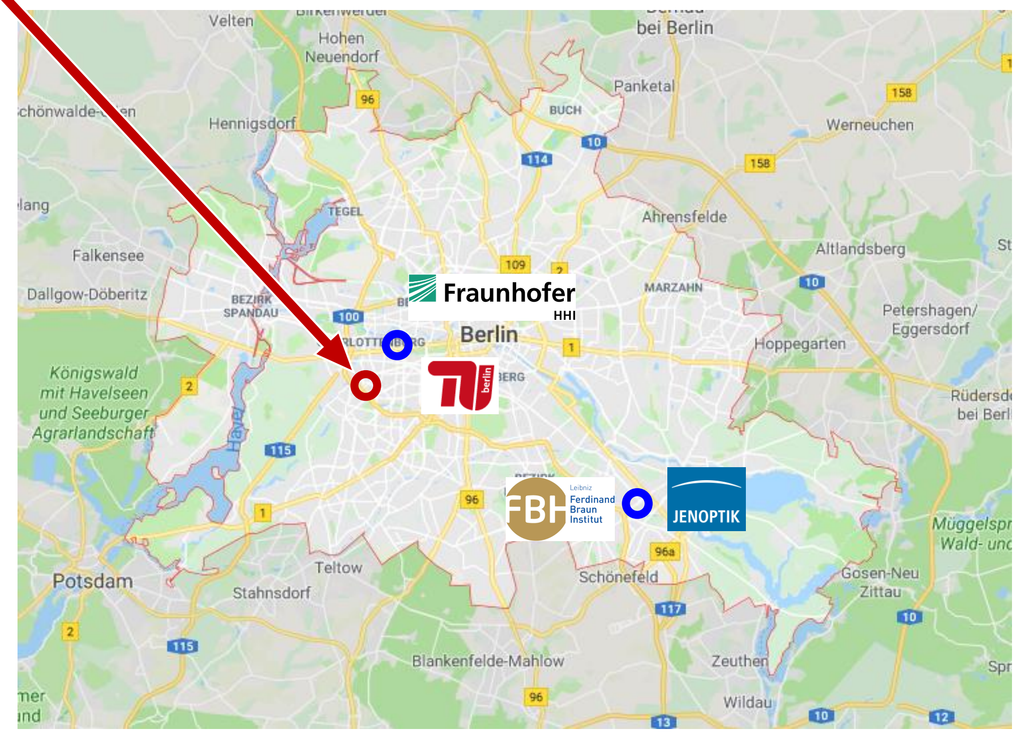
founded 1999 in Berlin
spin-off of TU Berlin
20 years old
65 employees
2500 systems sold
operating worldwide

NYNOMIC
THE PHOTONICS GROUP



https://www.google.de/maps

Our business: Process-integrated optical metrology

Our markets: Semiconductor and thin-film industry & academia incl. lighting, laser, photovoltaics, glass coating …

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Integrated metrology for various industries and markets

In-line

Conveyor,
Roll-to-Roll, in-chamber

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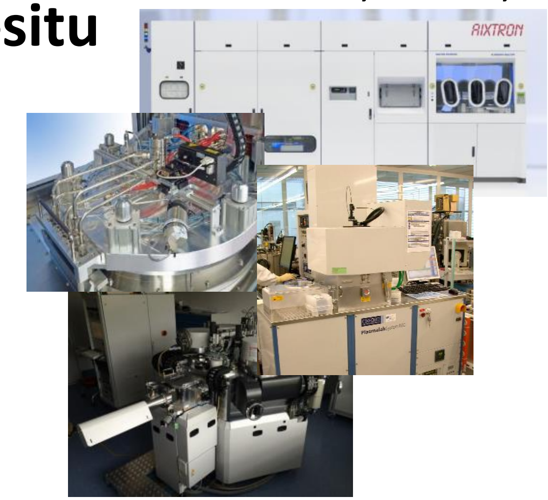
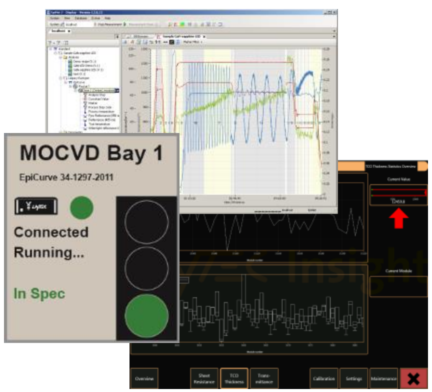
In-situ

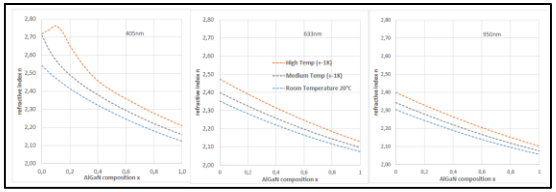
ALD, sputtering,
PECVD, MOCVD, …



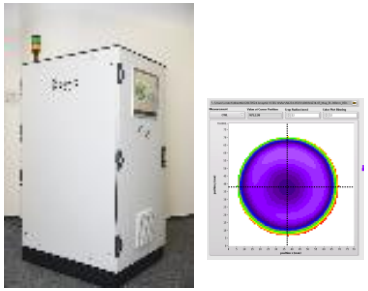


Software & Analysis

Simulation, analysis, fit, integration

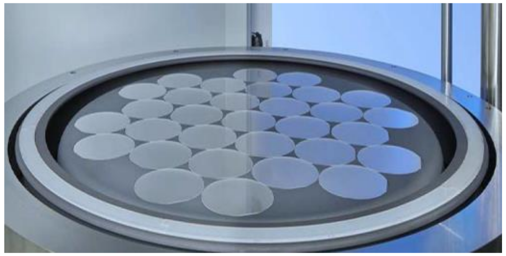


Material data base



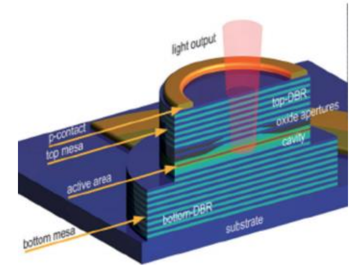
Mapping

in-situ metrology in semiconductor industry



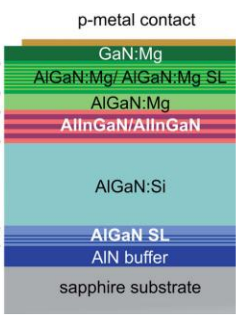
substrate wafers

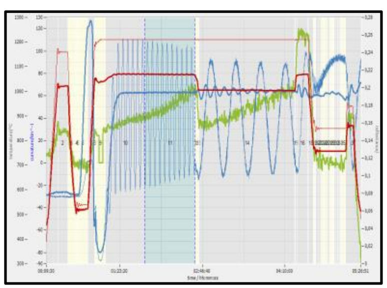
optical in-situ metrology tool



semiconductor device
(e.g. VCSEL)

process control
= monitoring and control of deposition or growth process



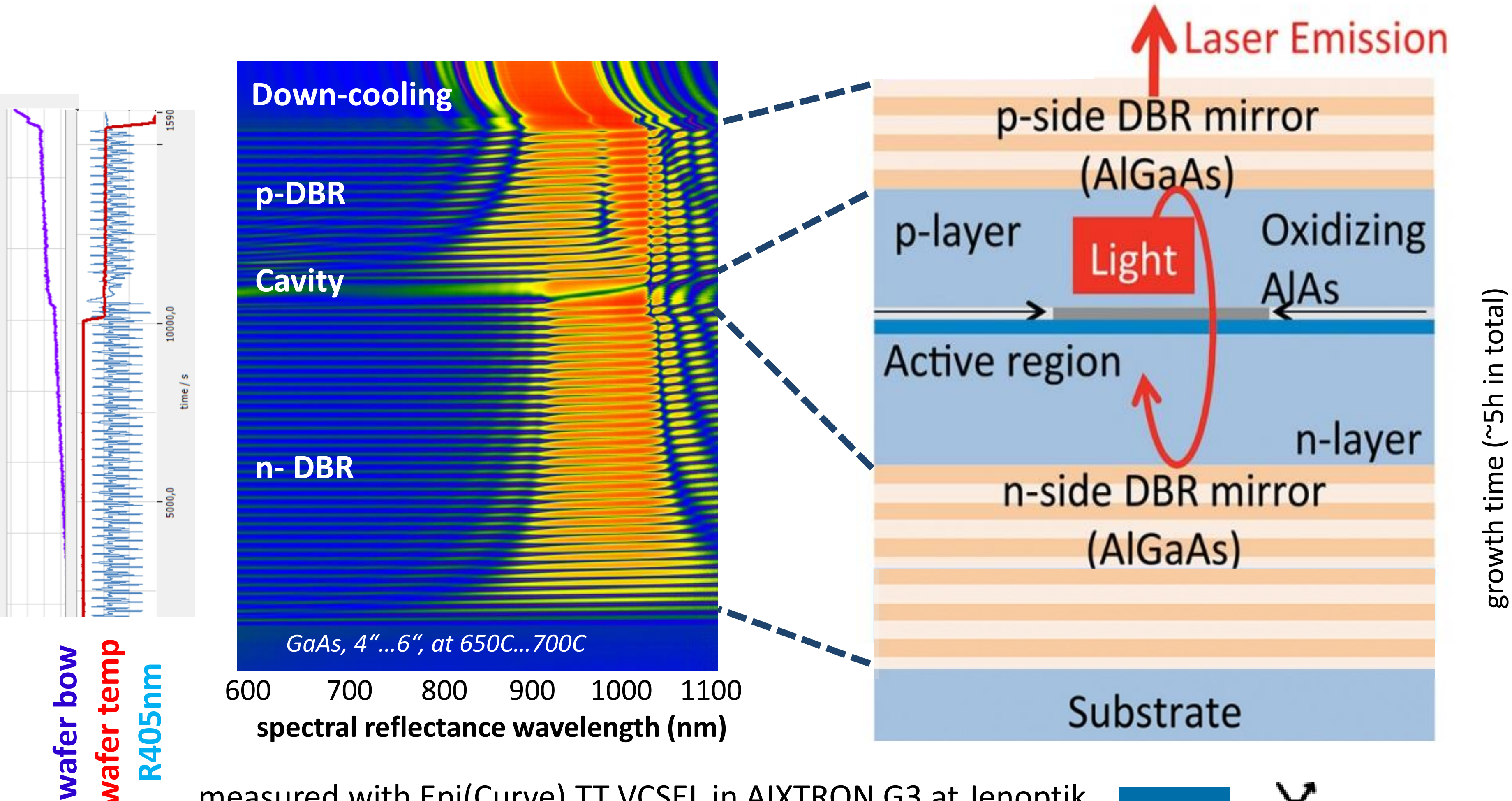


deposition system (e.g. MOCVD)

Measurement of
- **temperature**
- **layer thickness / growth rate**
- **ternary composition**
- **curvature / bow**
- **surface morphology**
- **spectral reflectance**

Example of in-situ metrology of a VCSEL structure

Goal: reliable prognosis of device properties by in-situ spectral reflectance



measured with Epi(Curve) TT VCSEL in AIXTRON G3 at Jenoptik

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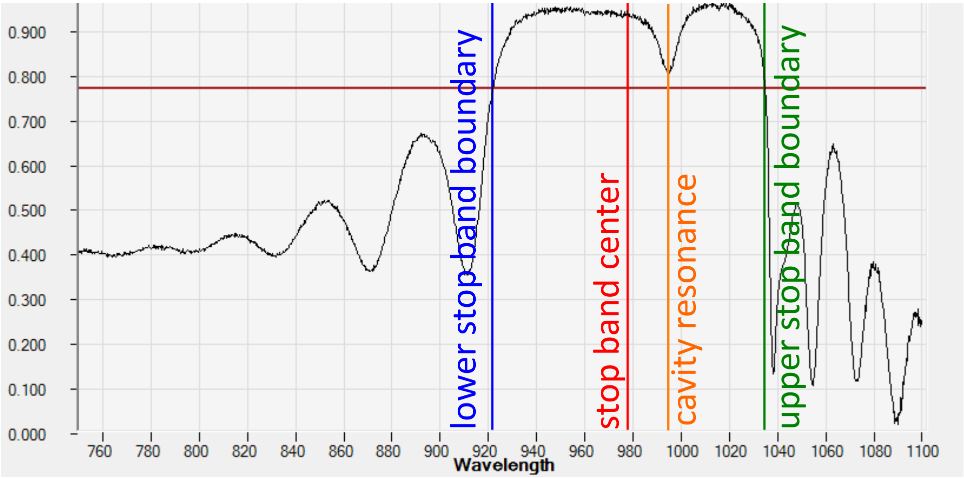
Example of in-situ metrology of a VCSEL structure

- Real-time analysis (during run) allows determination of parameters like stop band boundaries, stop band center and cavity resonance dip wavelength (+many more parameters)



Single reflectance spectrum during growth of p-DBR:

- thermal shift (+broadening)
- cavity resonance dip not in the center of the stop band
- In this case: recipe tuning needed
- But: a certain asymmetry is expected at T_{growth} because thermal shift (GaAs) > thermal shift (AlAs)

- Spectroscopic reflectance with time resolution of 100Hz enables determination of lateral homogeneity (center-edge comparison)

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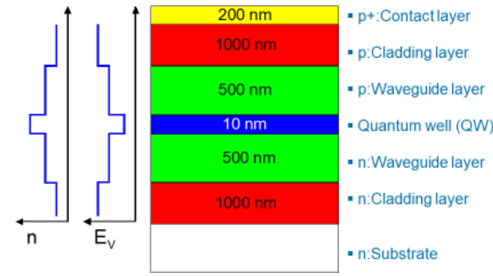
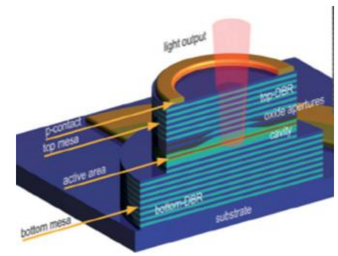
Current metrology challenges for VCSEL/DBR/SESAM

„Standard“ requirements
e.g. for **edge emitting lasers**
Growth rate = 0.500 ± 0.005 nm/s $\Rightarrow$ **~±1%**



Today‘s advanced requirements
e.g. for **VCSEL** emission wavelength (940 ± 1)nm
Growth rate = 0.5000 ± 0.0005 nm/s $\Rightarrow$ **~±0.1%**



High-yield manufacturing is not possible without in-situ metrology!
Epitaxy makes up ~80% of VCSEL production costs.

- >100 layers; >5µm stack
- thin layers (DBR, MQW)
- graded interfaces in DBRs
- pyrometry may be blocked by DBR

Tasks for in-situ metrology:

- spectral in-run analysis
- accuracy in growth rate measurement
- integration into MOCVD for advanced process control (such as feed-forward control)

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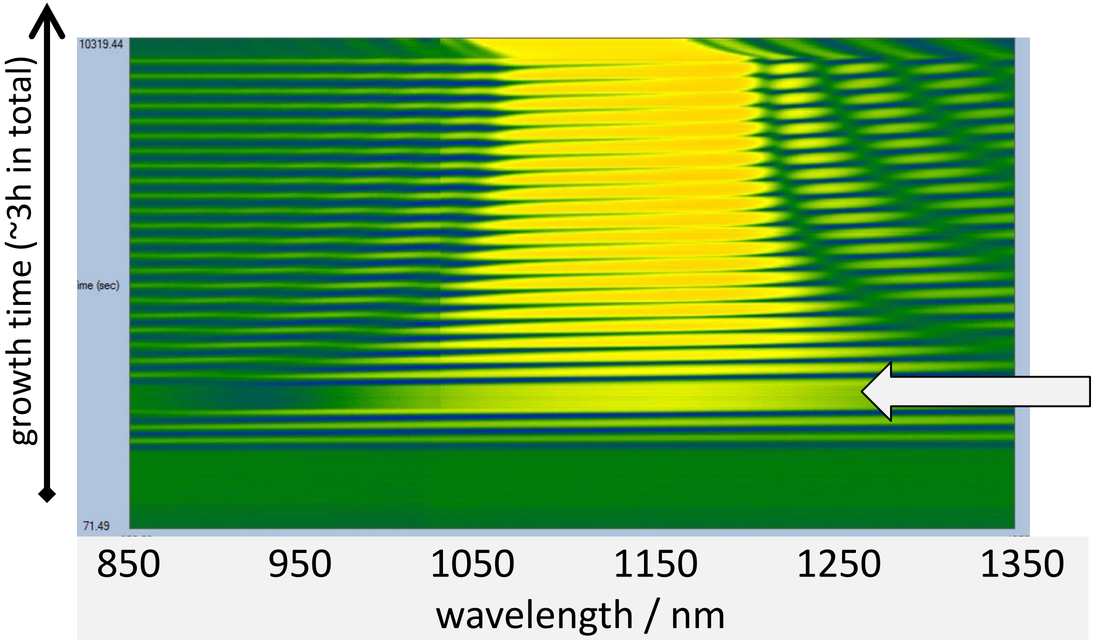
Example: SESAM (1030±1)nm – feed-forward control

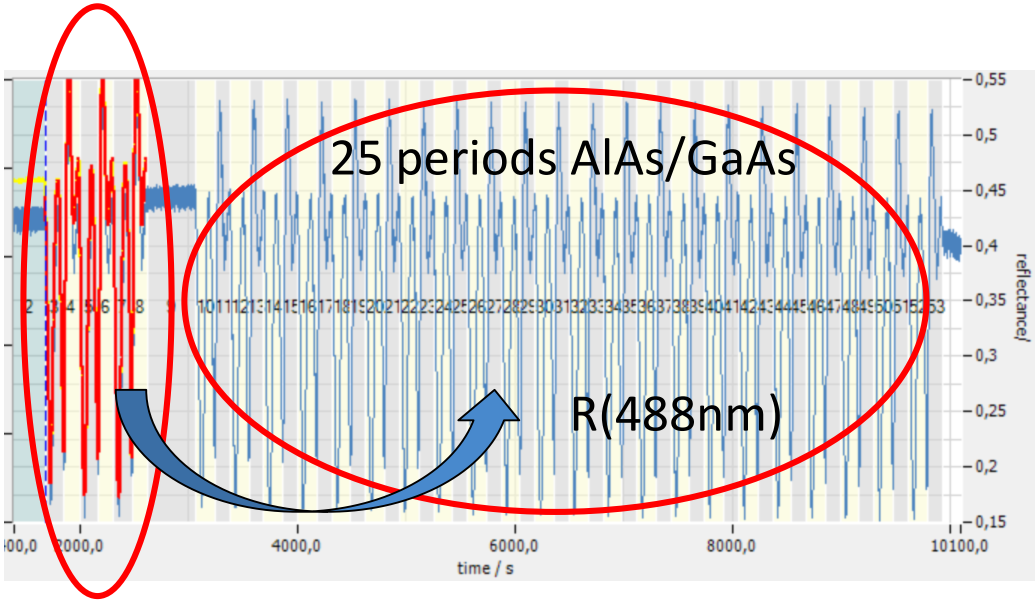
- SESAM: semiconductor saturable absorber mirror
- 25 pairs of GaAs/AlAs
- Full load in AIXTRON G3 reactor
- DBR Stop-Band: 990-1090nm (RT); 1030-1200nm (high T, up-shifted)

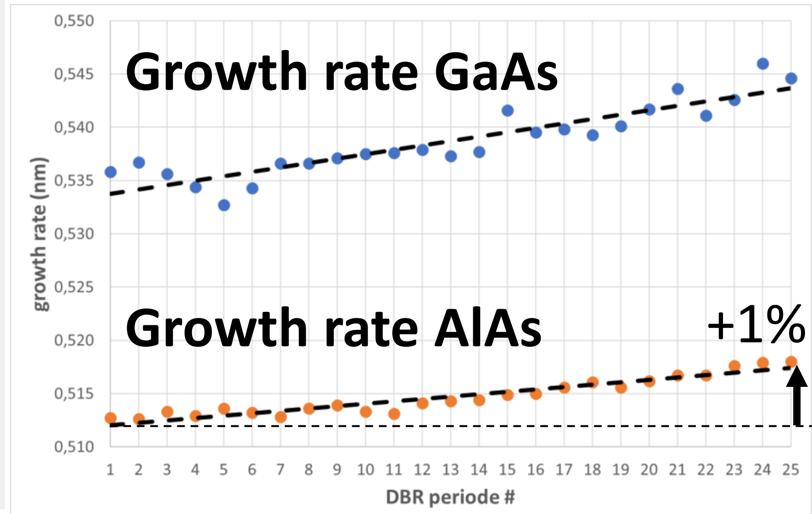


Spectral reflectance finger-print (850-1350nm, ~3h of epi, cool-down wavelength shift is seen)

Epi pause - for 6-layer (3 DBR periods) growth rate analysis and recipe feed-forward update

Example: SESAM (1030±1)nm – feed-forward control





- Determine growth rates of GaAs and AlAs during first 3 DBR periods
- Transmit growth rate to growth system
- Update growth times in recipe („feed forward")
- grow remaining 22 periods

- Detailed analysis of in-situ data show linear increase of growth rates over 25 periods
- Tiny effect, but important
- Must be taken into account to achieve desired accuracy

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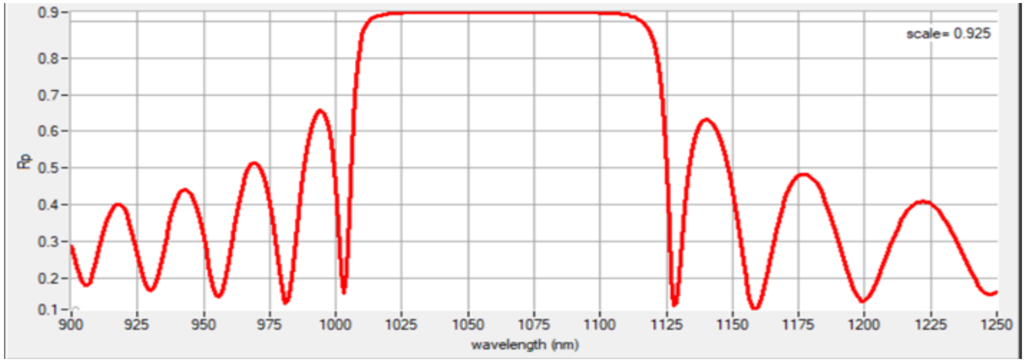
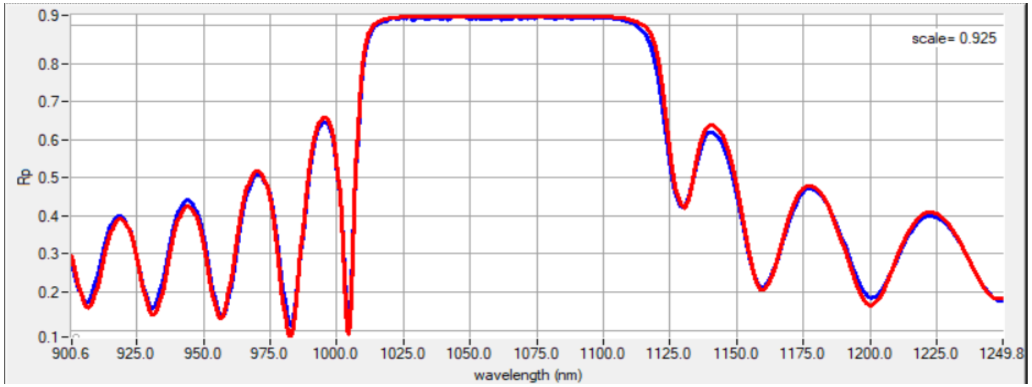
Example: SESAM - ex-situ growth rate analysis



Calculated reflectance spectrum of ideal DBR would be highly symmetric

Growth rate $_{GaAs}$ = 0.497 nm/s
Growth rate $_{AlAs}$ = 0.580 nm/s



Blue: Measured DBR spectrum; asymmetric

Red: Analytic model based on in-situ measured growth rates with linear increase

Growth rate$_{GaAs}$ = 0.4955 nm/s → 0.4990 nm/s (+1% from start of DBR to end of DBR)
Growth rate$_{AlAs}$ = 0.5769 nm/s → 0.5839 nm/s (+1% …)

Excellent agreement to measured ex-situ reflectance spectrum

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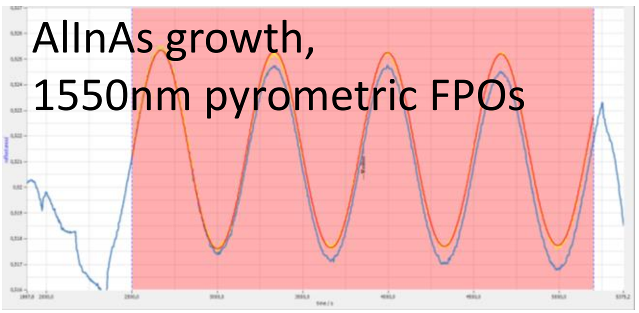
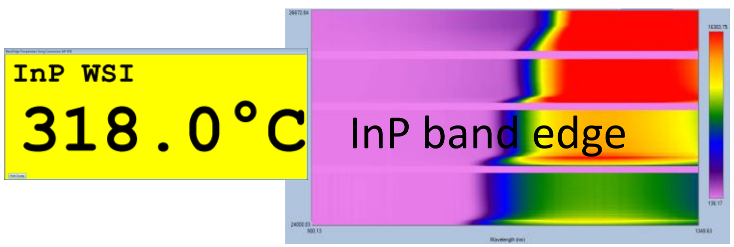
Acknowledgements & Cooperations

Martin Zorn
JENOPTIK Diode Lab GmbH, Berlin, Germany

Andre Maaßdorf, Markus Weyers
Ferdinand-Braun-Institut, Berlin, Germany

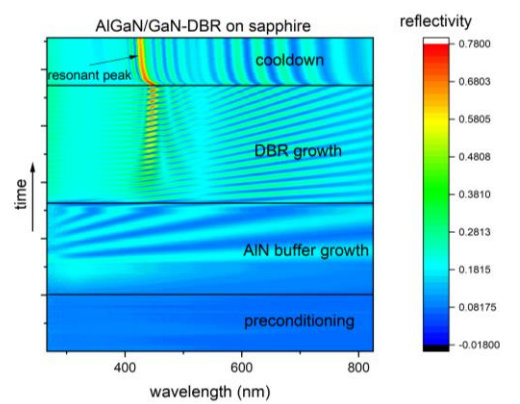




Helping the WSI Munich to transfer growth processes for long wavelength VCSELS from research MBE to production MBE:

- precise growth rate determination using pyrometric FPOs
- GaAs/InP band edge temperature system to transfer exact process temperatures

Metrology for GaN-based VCSELs (EpiTT VCSEL UV)



Summary…

- We have developed new spectroscopic analyses for resonant structures and new procedures for measuring the growth rates of thin layers (with composition grading) in highly complex device structures.
- High-yield manufacturing of current cutting-edge devices like VCSEL/ DBR/ SESAM can only be facilitated by close integration of in-situ metrology into the MOCVD tools (e.g. feed-forward control schemes).
- Ex-situ mapping of Epi uniformity achieves a new level of accuracy by feeding in the results of in-situ analysis.

… and beyond

- We are looking for close collaborations with VCSEL foundries and their customers, e.g.:
  - develop and test new comprehensive control concepts
  - use in-situ results for advanced mapping schemes

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This presentation was presented at EPIC Meeting on VCSELs Technology and Applications 2019

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