State-of-the-art in-situ metrology during OMVPE in academic research and industry

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Knowledge is key

Acknowledgements

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Outline

In-situ metrology for MOCVD – a brief sketch of historical development

Current metrology challenges

State-of-the-art metrology for VCSEL/DBR/SESAM

UV-LEDs: in-situ metrology for high Al-containing III-Ns

Summary and outlook

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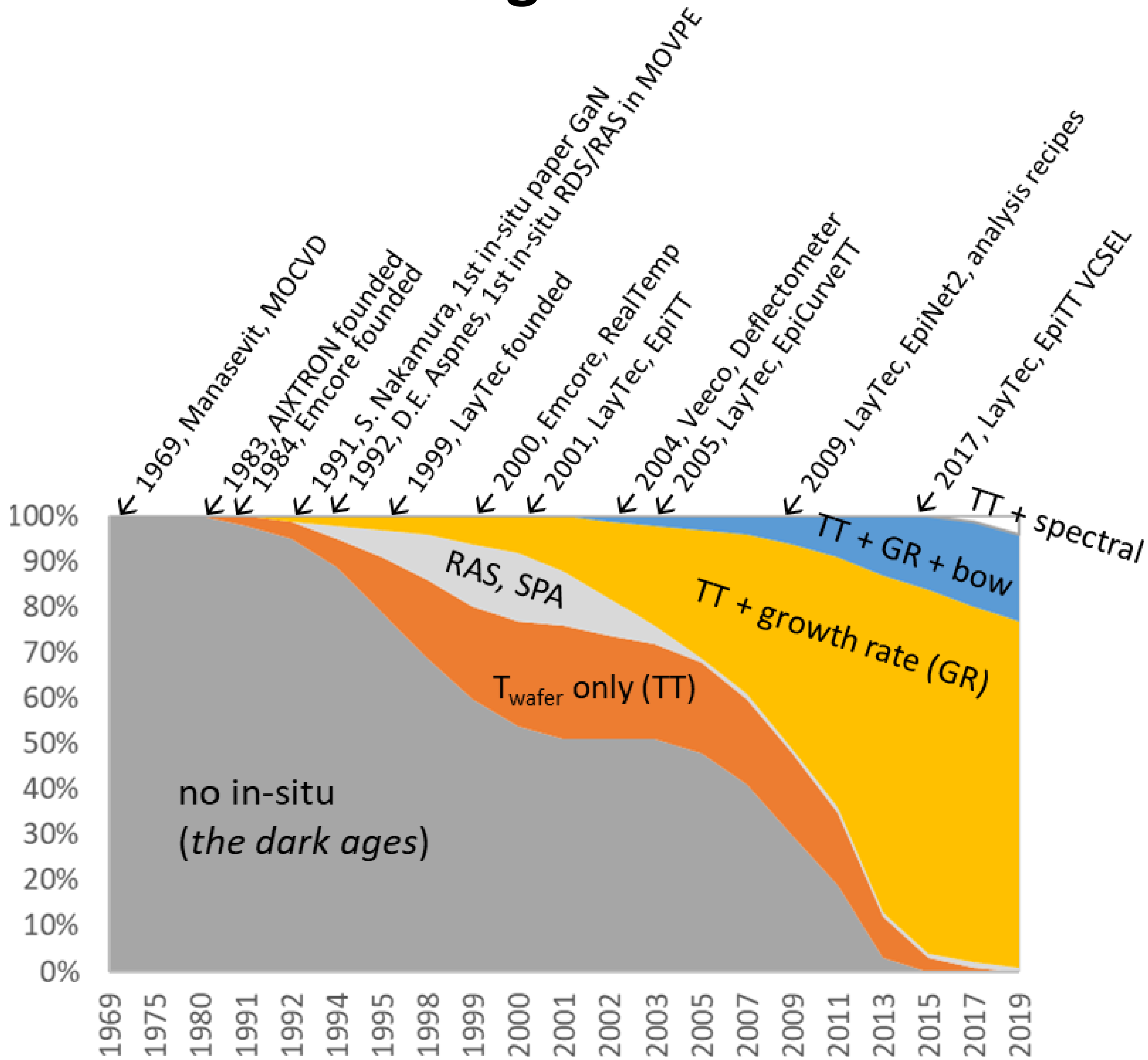
In-situ monitoring for MOCVD – historical development

Carl Spitzweg: "Der Alchimist" (1860)

In-situ monitoring for MOCVD – historical development



RAS = reflectance anisotropy spectroscopy

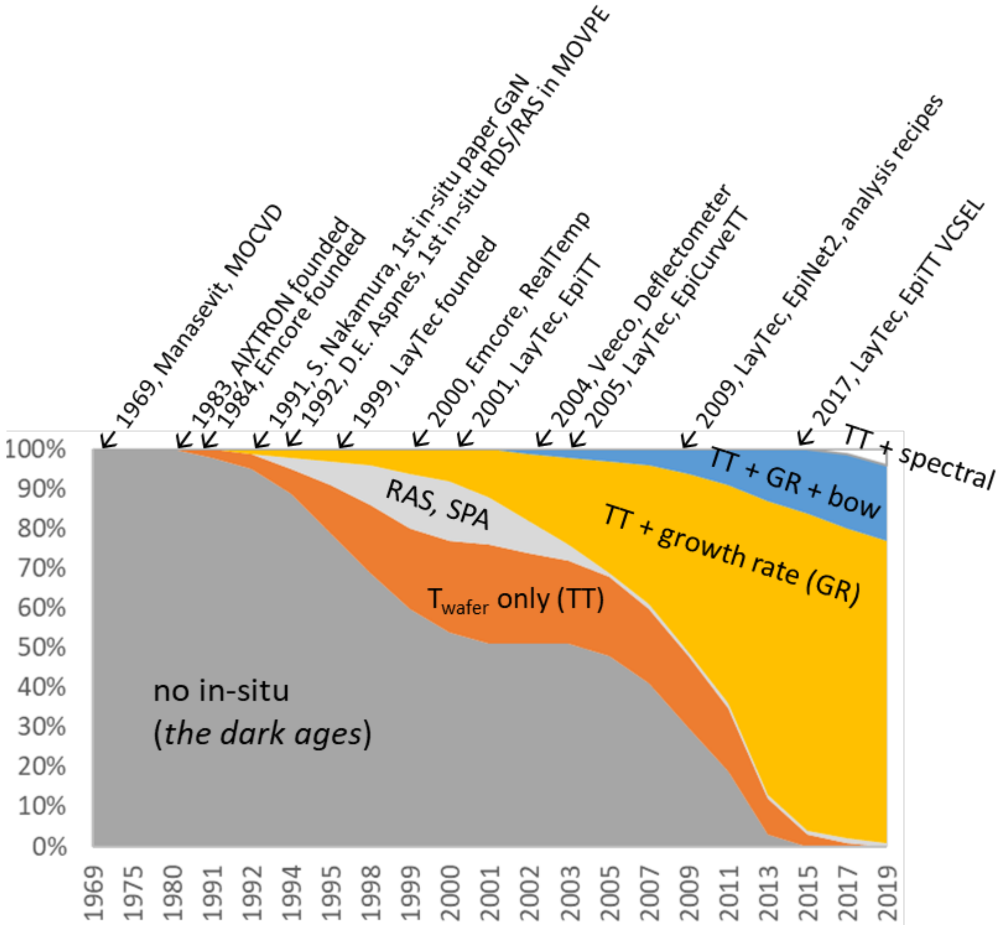
SPA = surface photo absorption

TT = true temperature measurement

GR = growth rate measurement

bow = wafer bow/curvature measurement

In-situ monitoring for MOCVD – historical development



Ben Stevens et al. (IQE), CSManTech, May 2019:

"**All VCSEL reactors at IQE use a LayTec EpiTT** … The LayTec system also **enables characterization of critical layers in a VCSEL that could not be characterized by traditional means** or would require complicated modelling. **Through use of analysis recipes the required analysis can be loaded into the MES before the wafers are even unloaded from the reactor**."

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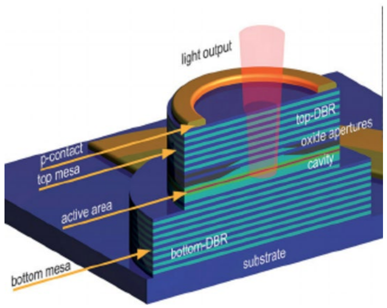
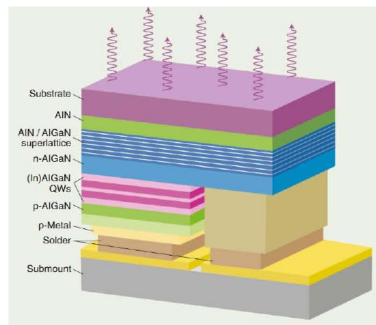
VCSEL on GaAs



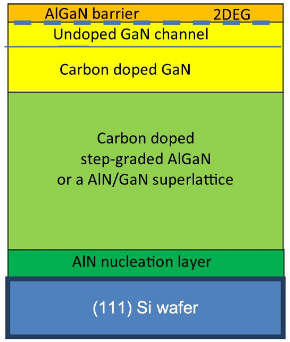
- >100 layers; >5µm stack
- 0.1% accuracy in growth rate
- pyrometry blocked by DBR
- x_{AlGaAs} for oxide aperture
- **graded interfaces** in DBRs
- nm-scaled layers (MQW, grading)

UV-C LED on sapphire



- 2-step epi (AlN/sapph + LED)
- >3µm stack
- all layers k=0
- no access to T_{wafer}
- **surface roughness (x_{AlGaN} >0,5)**
- High strain (AlGaN on AlN)
- nm-scaled layers (MQW, SL, EBL)

GaN Power HEMT on Si



- Large wafers + large bow
- Pyrometry: GaN is ARC on Si, 40% oscillations in emissivity
- >3µm stack, all layers k=0
- **Wafer temperature during AlGaN barrier growth** extremely critical

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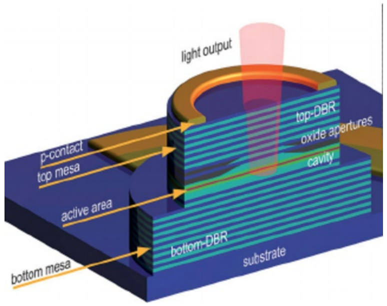
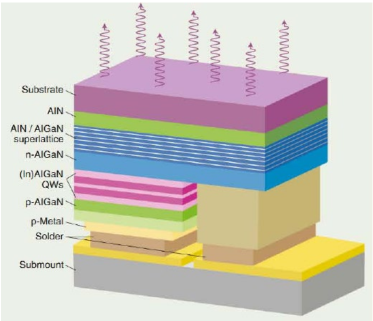
Current metrology challenges

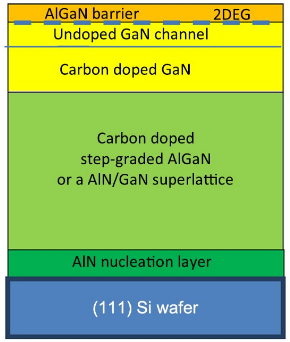
VCSEL on GaAs



UV-C LED on sapphire



GaN Power HEMT on Si



These three very different device structures have in common:

- >5 hours of Epi
- wafer temperature measurement is very difficult
- high-yield manufacturing is not possible without in-situ metrology

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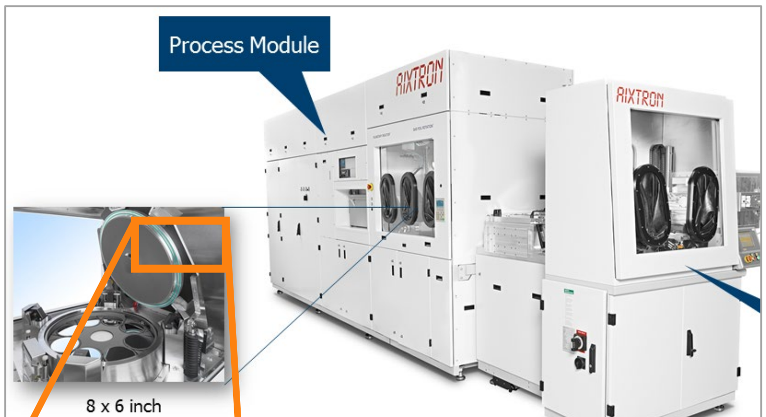
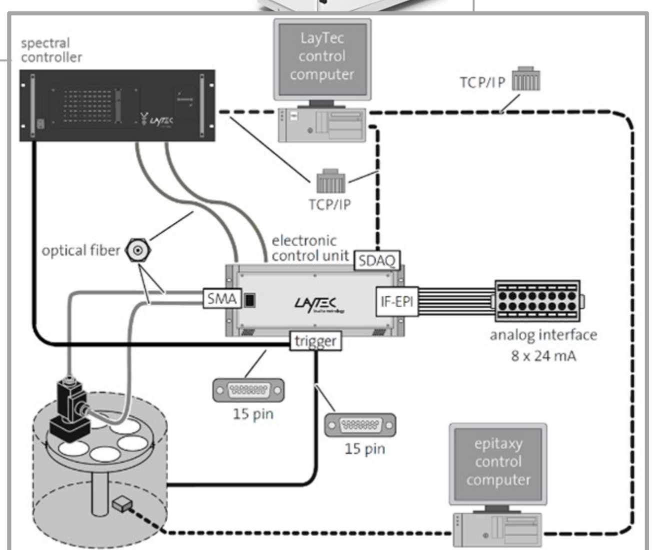
Market leading MOCVD tool for VCSELs, GaN/Si HEMTs: AIXTRON planetary G4/G5



In-situ tool



Integration concept

This success is supported by recent advances in in-situ metrology:

- Highly precise measurement of growth rates even for very thin layers in sophisticated multi-layer structures
- Recipe controlled automated in-situ data analysis, synchronized to epi recipe, interfaced to MES
- Metrology based feed-forward of wafer temperature for satellite rotation control in long and complex device runs

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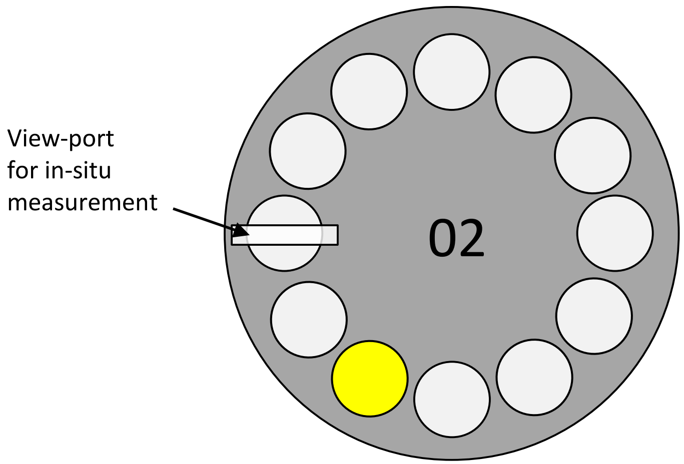
How to measure thin layers in a multi-wafer reactor?

Example: DBR interface layers in 940nm VCSEL

6 … 15nm graded AlGaAs, typical growth times of 12 … 30s

Typical susceptor rotation: 10 rpm, 12x3“ configuration



= Data acquisition every 6s

= 2 data points in 12s of growth
for a single wafer … not enough!

Knowledge is key

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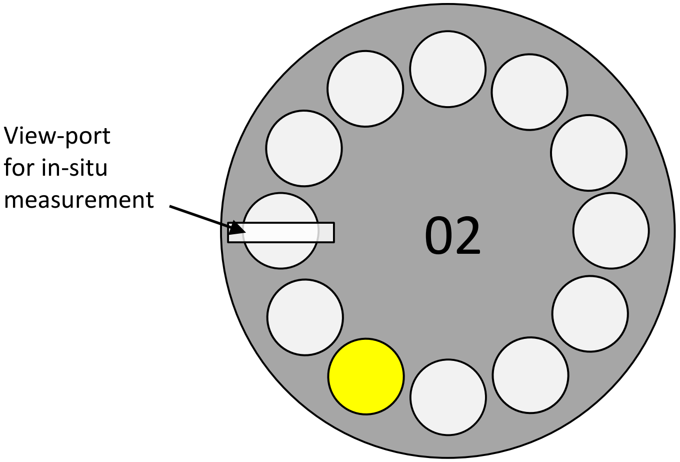
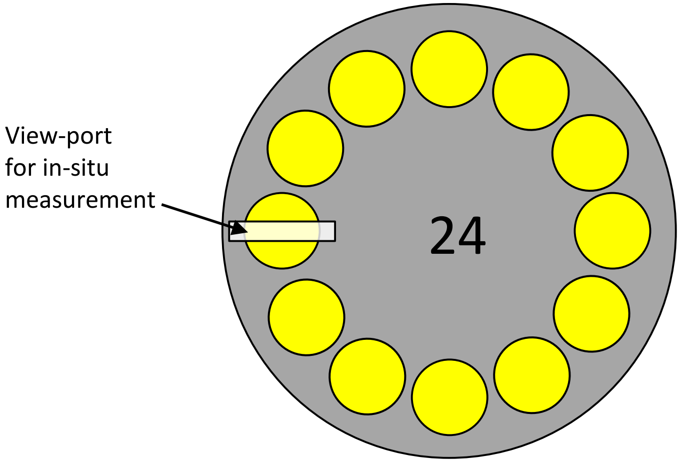




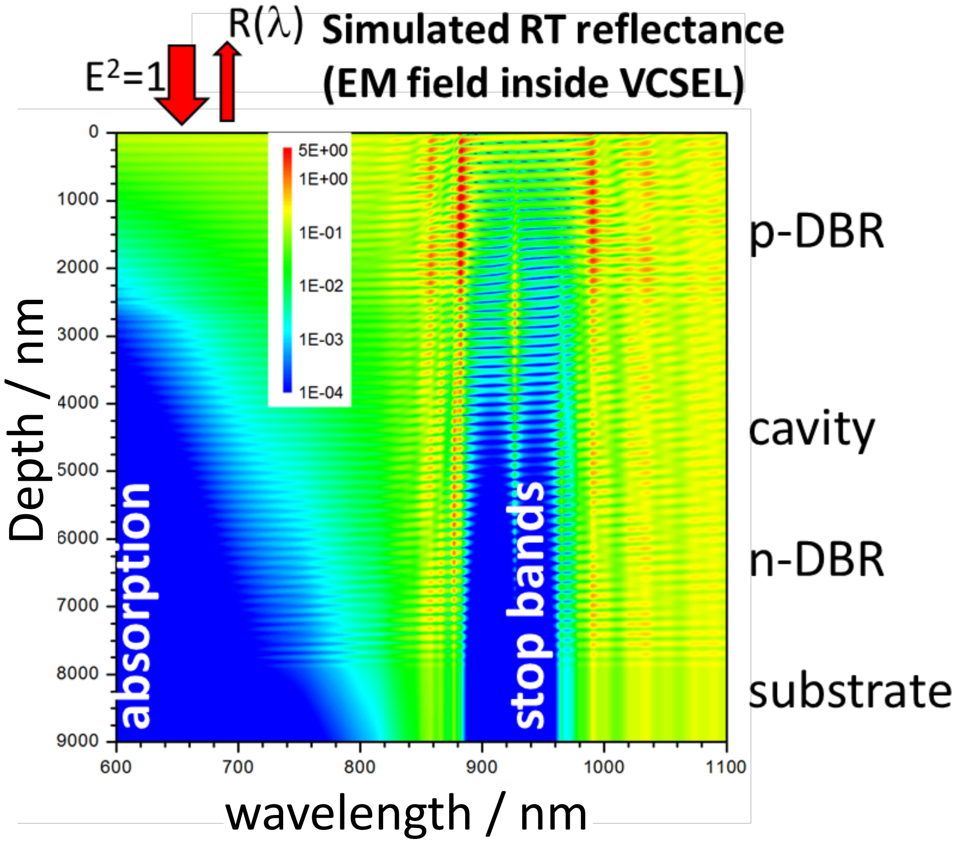
= Data acquisition every 6s
= 2 data points in 12s of growth
for a single wafer … not enough!

with „merged data“:
= data acquisition every 0.5s
= 24 data points in 12s of growth

Merged dataline mode: A must for nm-scaled layers

Can we consider all wafers to be identical?
Yes, if we use the right wavelength!

Analysis of light penetration depth



$\lambda > \lambda_{E0}$: k~0

→ light penetrates all of the complex layer structure

→ tiny differences (wafer-to-wafer) accumulate

→ merged datalines are getting „noisy“

$\lambda << \lambda_{E0}$: k>0

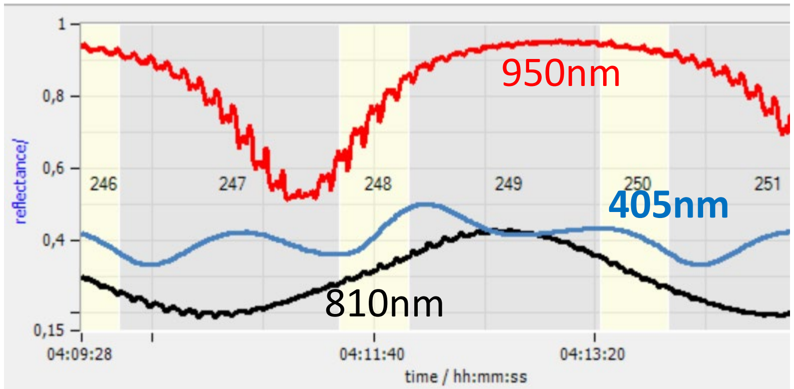
→ light penetrates the uppermost layers only

→ growth highly uniform

→ cutting-edge S/N of in-situ reflectance

Wavelength selection for high-accuracy growth rate monitoring of thin layer

- Longer wavelength penetrate through whole stack = wafer-to-wafer differences accumulate
- Shorter wavelength are sensitve to uppermost layer(s) only



after 4h of VCSEL epi (end of p-DBR)

Data: EpiCurveTT VCSEL at Aixtron G3 11x3"/1x4" (Jenoptik)

Experimental proof in AIX G3

← long wavelength („noisy")

← short wavelength (no „noise")

Use short wavelength for growth rate monitoring of very thin layers

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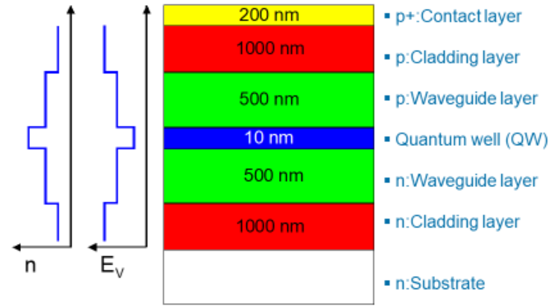
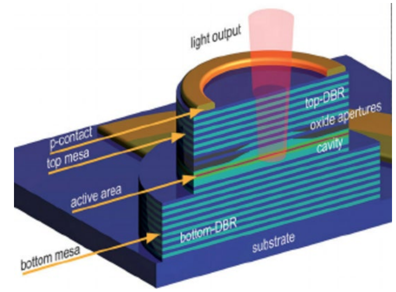
Current metrology challenges for VCSEL/DBR/SESAM

„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%**



- >100 layers; >5µm stack
- thin layers (DBR, MQW)
- graded interfaces in DBRs

Tasks for in-situ metrology:
- Accuracy in growth rate measurement
- integration into MOCVD for advanced process control (such as feed-forward control)

VCSEL	vertical cavity surface emitting laser
DBR	distributed Bragg mirror
SESAM	semiconductor saturable absorber mirrors

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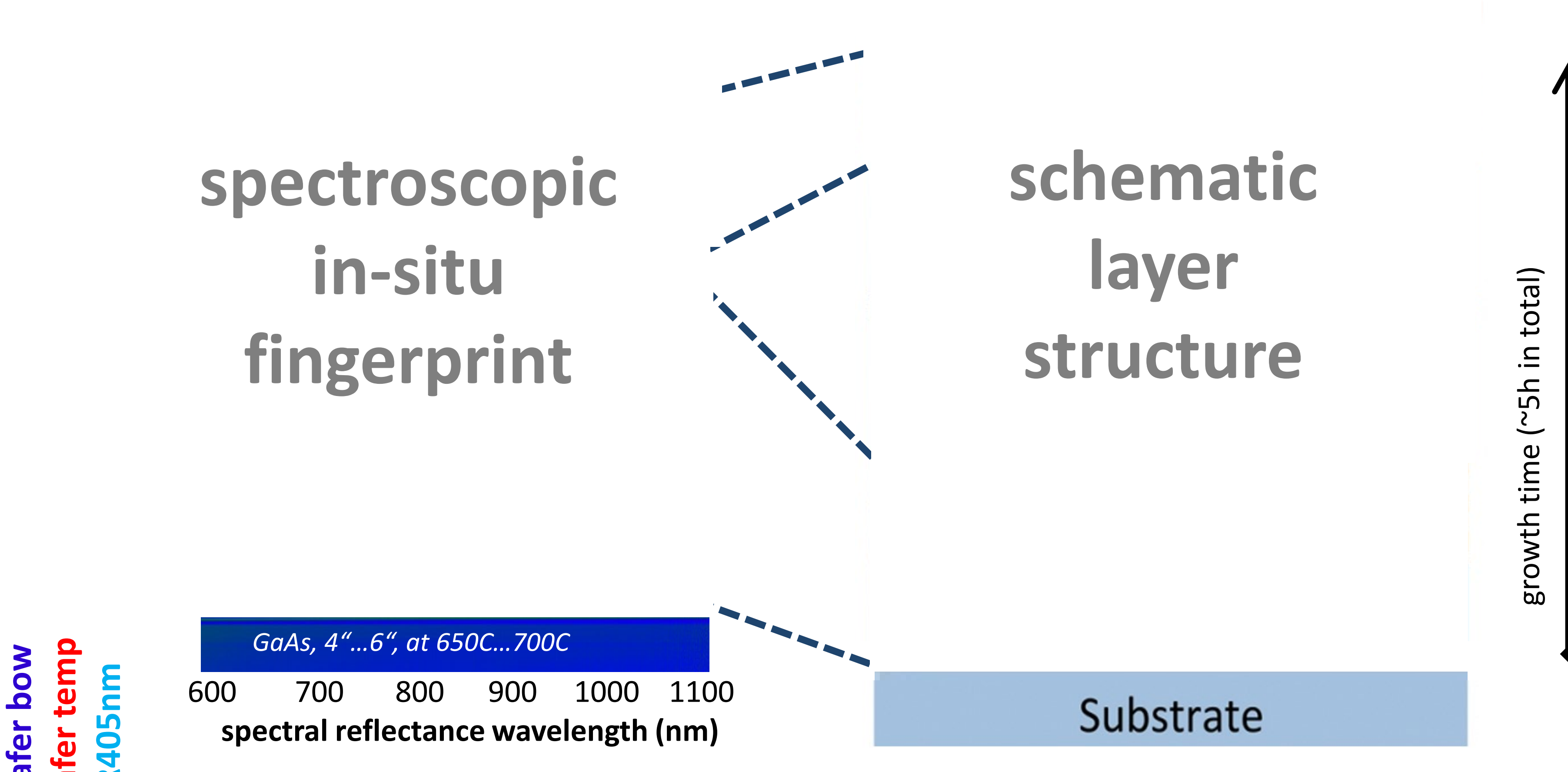
Example of in-situ metrology of a VCSEL structure

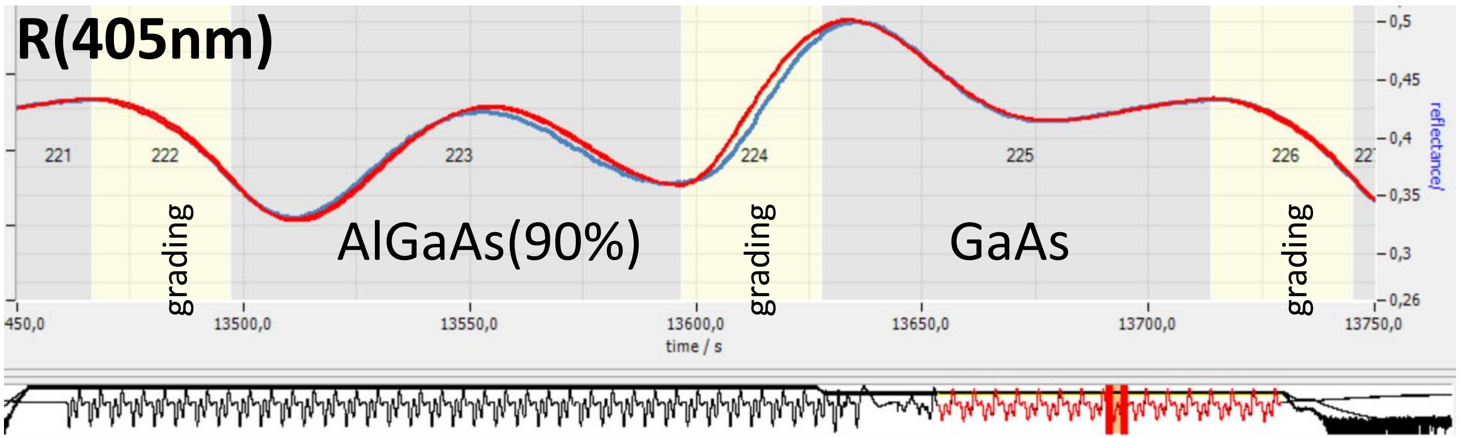
Goal: reliable prognosis of device properties by in-situ spectral reflectance



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

Example 1: Interface grading in 940nm VCSEL DBR

Approach:
model-based fit of measured reflectance curves for growth rate analysis



p-DBR
lower T_g

Blue: measured
Red: fitted

slow grading (30s)
Model: linear grading

Good agreement with linear model

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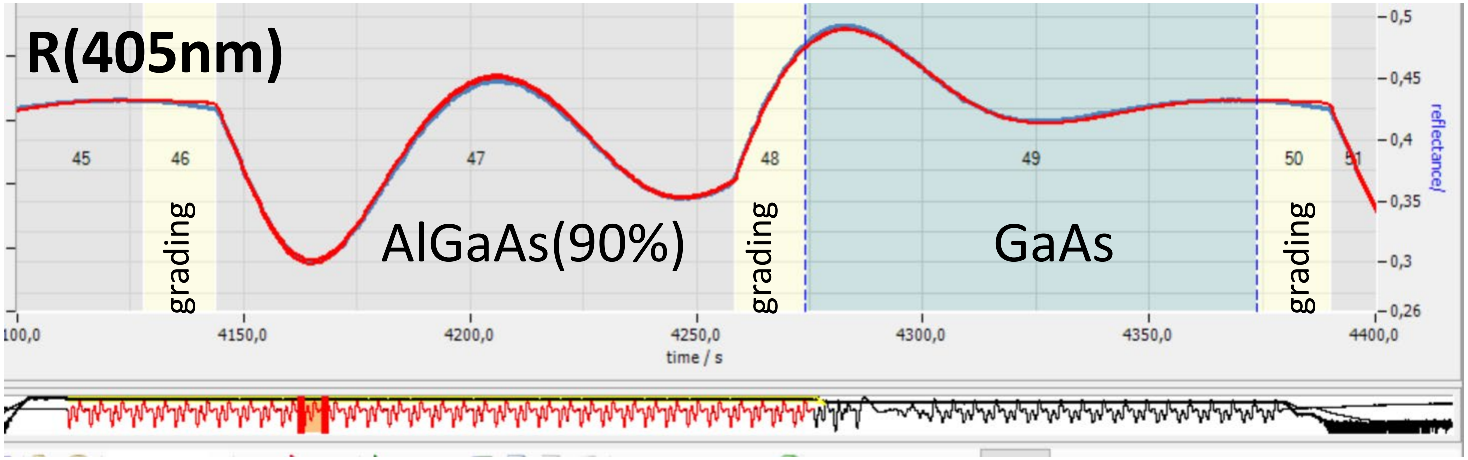
Example 1: Interface grading in 940nm VCSEL DBR

Approach:
model-based fit of measured reflectance curves for growth rate analysis



n-DBR
higher T_g

Blue: measured
Red: fitted

Fast grading (16s)
Model: no grading

Linear change in TMG/TMA gas-flow not always leads to linear grading in x_{AlGaAs}

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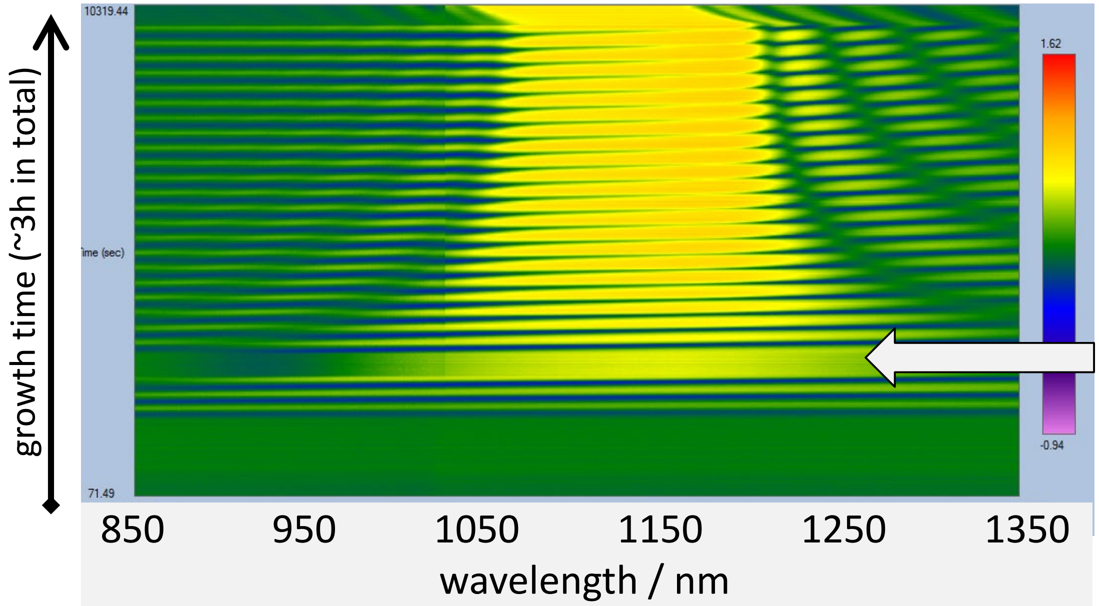
Example 2: SESAM (1030±1)nm – feed-forward control

- 25 pairs of GaAs/AlAs
- Full load in AIXTRON G3
- DBR Stop-Band: 990-1090nm (RT); 1030-1200nm (high T, shifted)
- Monitored by wide spectral range version (488, 633, 700-1500nm) of EpiCurveTT VCSEL



Spectral reflectance finger-print (800-1350nm, ~3h of epi, cool-down wavelength shift is seen)

Epi pause - for 6-layer growth rate analysis and recipe feed-forward update

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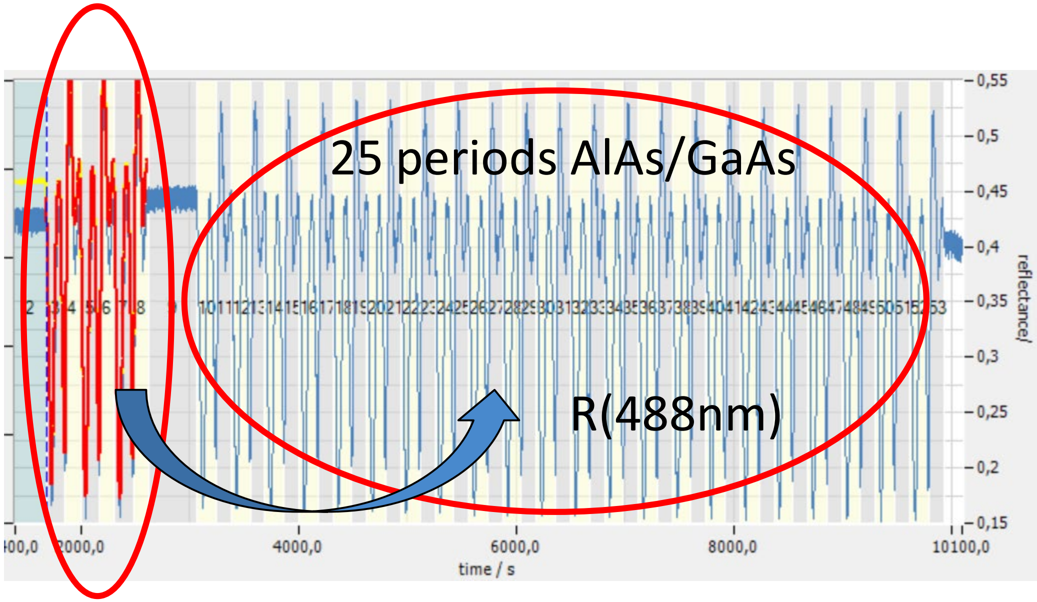
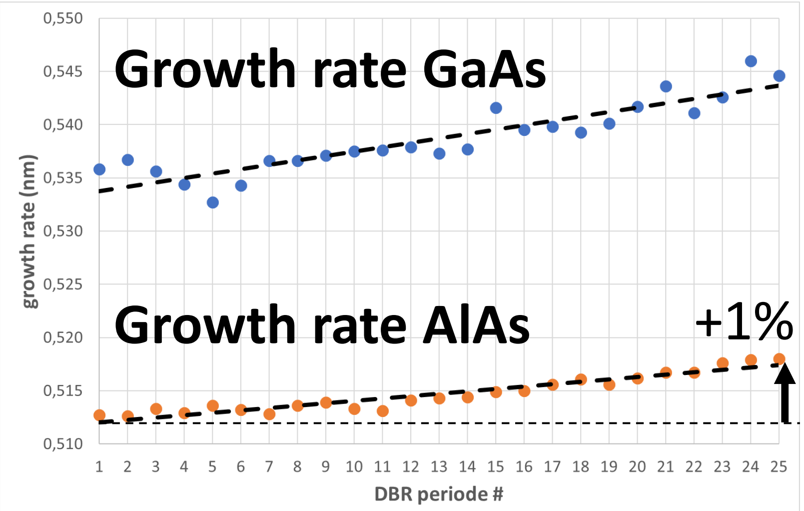
Example 2: SESAM (1030±1)nm – feed-forward control





- 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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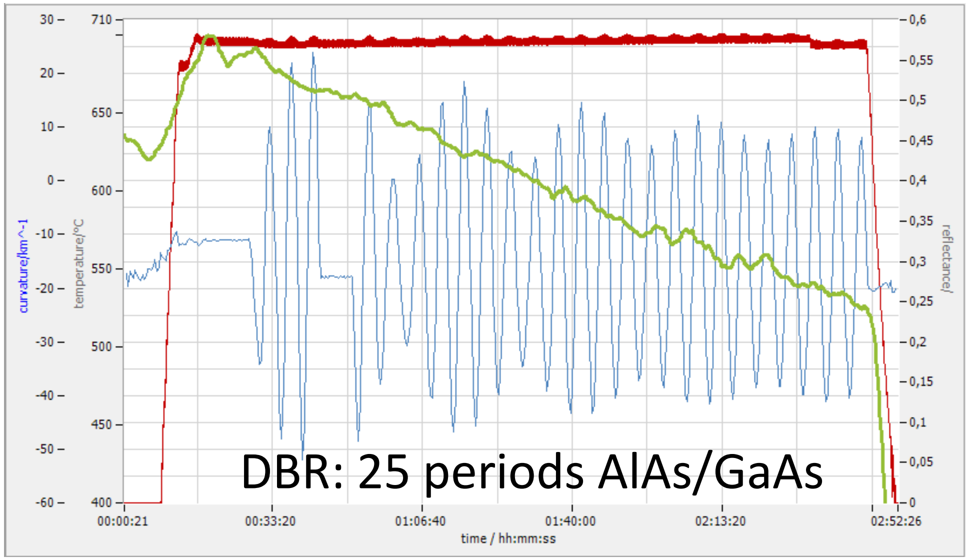
Example 2: SESAM (1030±1)nm – feed-forward control

Why is growth rate slightly changing during DBR?



True Temperature

Reflectance 950nm

Curvature

- Wafer is bowing during DBR growth (compressive strain in AlAs/GaAs stack)
- Thermal emission of wafer is reduced (growing DBR is covering GaAs band-edge wavelength) → reduced cooling by radiation
  → wafer temperature is increasing by ~4K
  → AIXTRON's AFF technology needed to compensate

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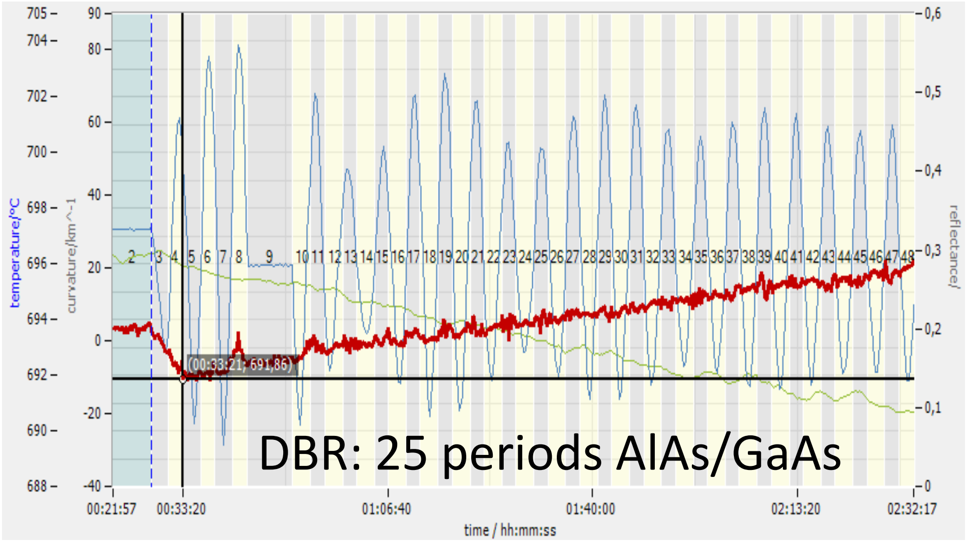

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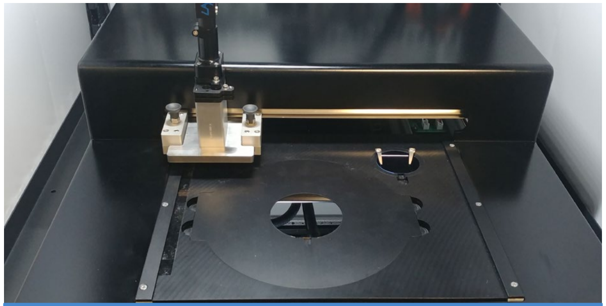
- Thermal emission of wafer is reduced (growing DBR is covering GaAs band-edge wavelength) → reduced cooling by radiation
  → wafer temperature is increasing by ~4K
  → AIXTRON's AFF technology needed to compensate
- And other effects …

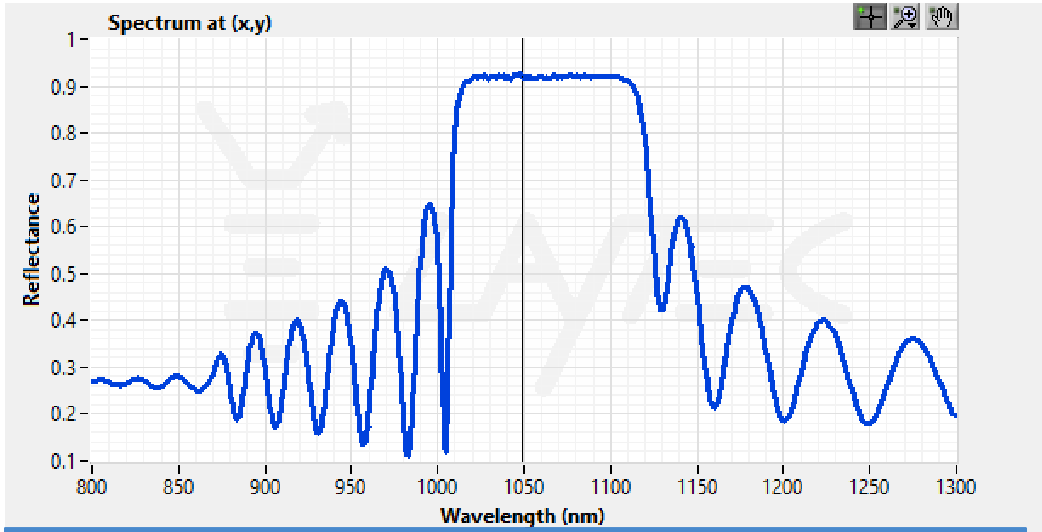
Example 2: Verification by ex-situ mapping

LayTec EPIX system



Mapping stage, 3“ sample holder plate

Mapping station EPIX combines white light reflectance and PL (multi-head mapping)



SESAM DBR, center of wafer, white-light reflectance

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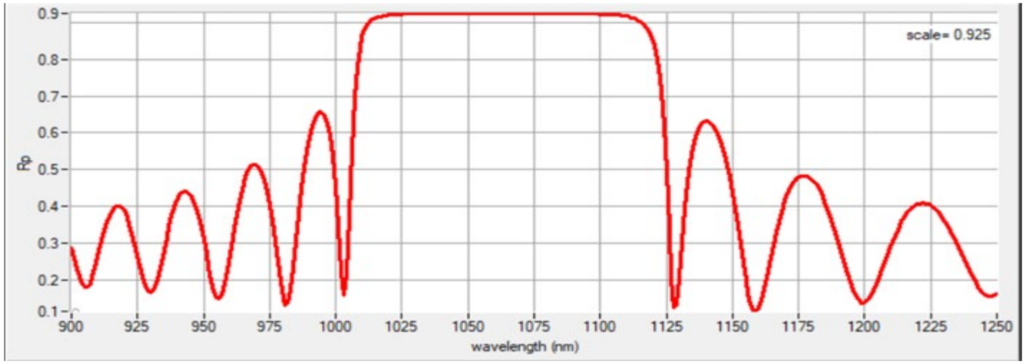
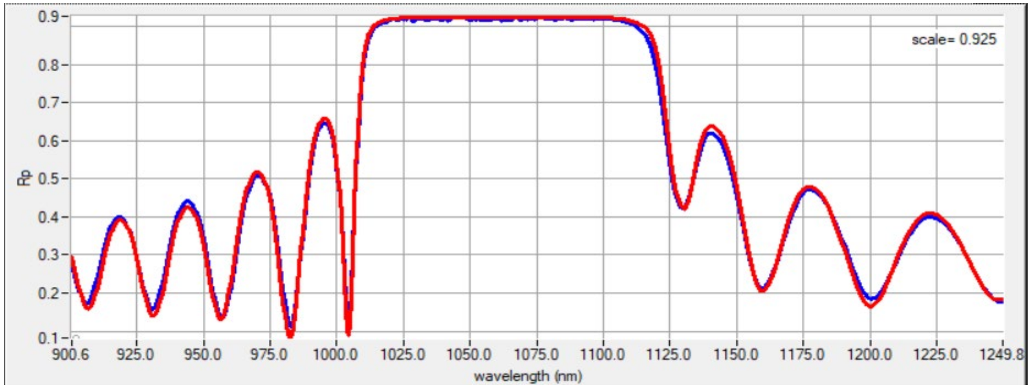
Example 2: Ex-situ growth rate analysis in wafer center



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 in wafer center

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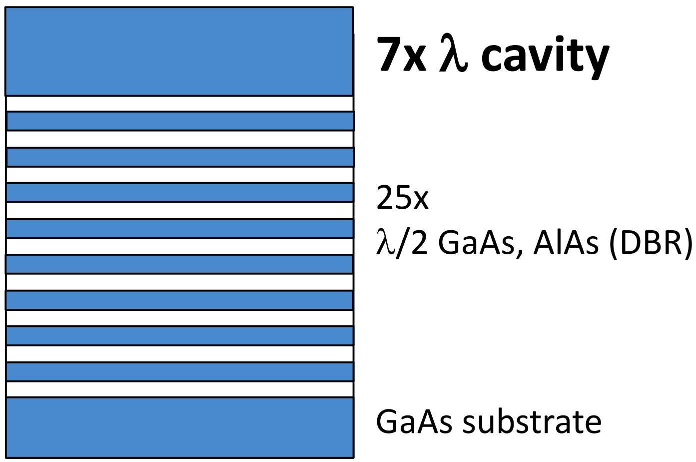
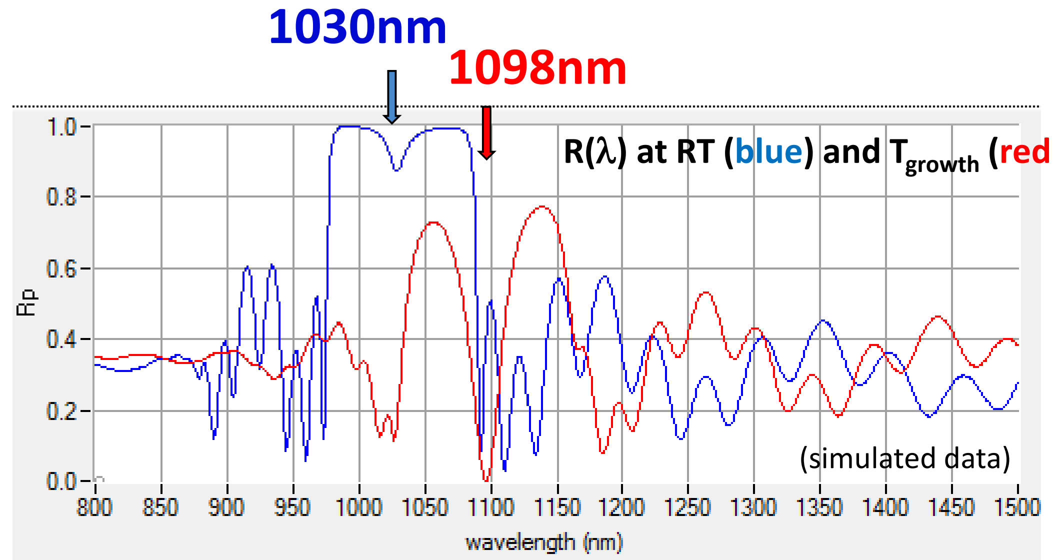
Example 3: cavity end-point detection for 1030nm SESAM





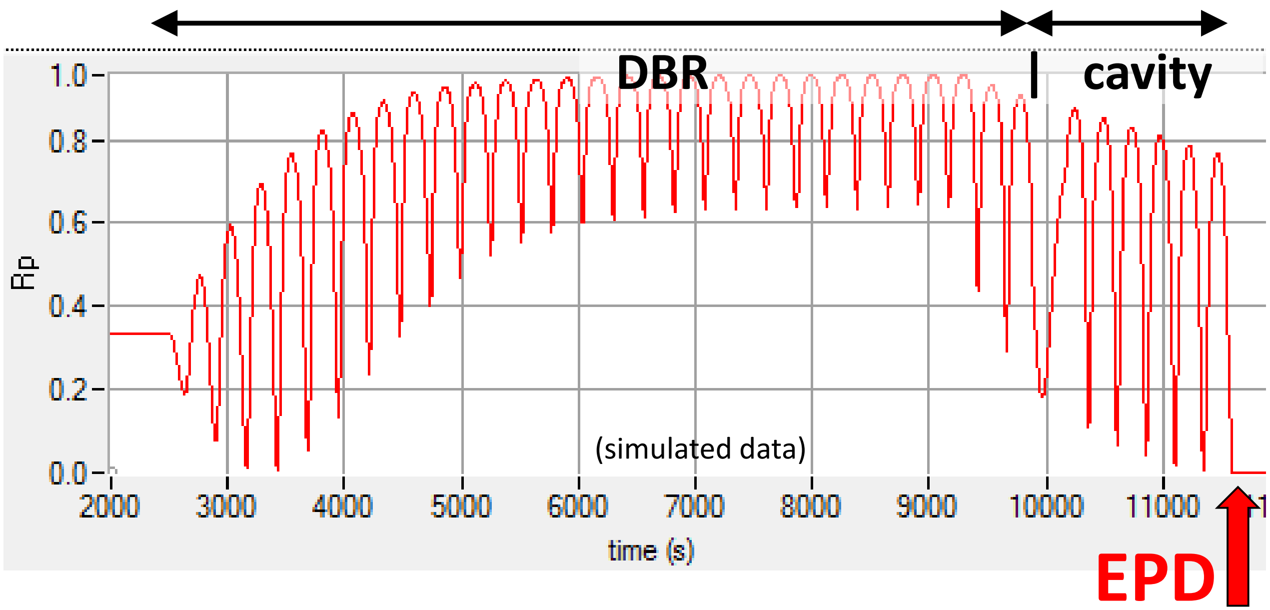
Goal: Grow cavity with thickness of exactly 7 λ for λ=1030nm

Problem: At growth temperature cavity dip and stop band are shifted to longer wavelength
i.e. end-point control at 1030nm is useless

Solution: Select shifted wavelength of cavity resonance at T_{growth} for end-point detection (EPD) of cavity thickness: 1098nm

Example 3: cavity end-point detection for 1030nm SESAM

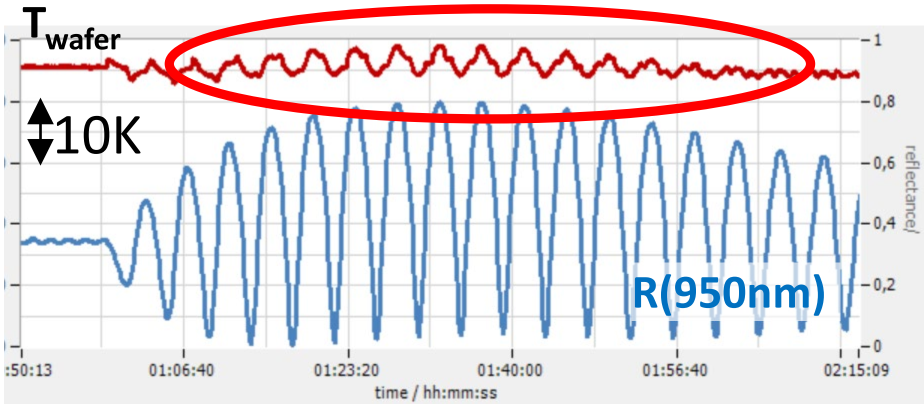
1098nm in-situ transient



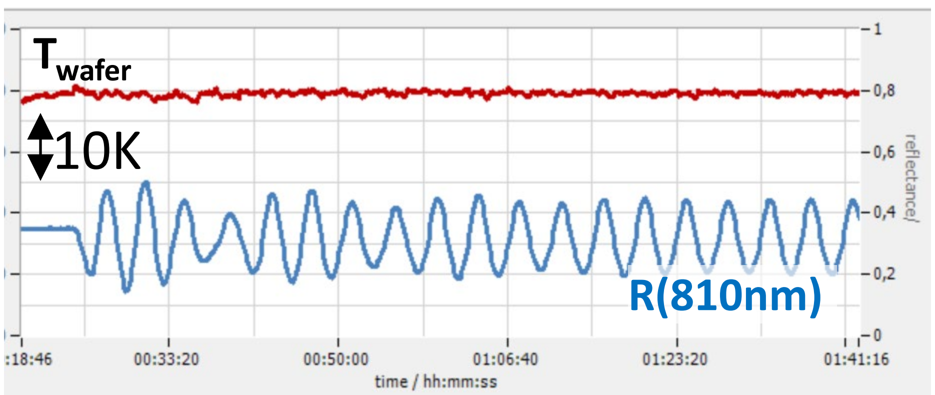
- Monitor reflectance at 1098nm
- Stop growth when reflectance curve goes through 7th minimum

- **Full spectroscopic measurement allows free choice of ideal wavelength for end-point detection (EPD)**
- **± 1nm accuracy in cavity dip – possible by EPD**

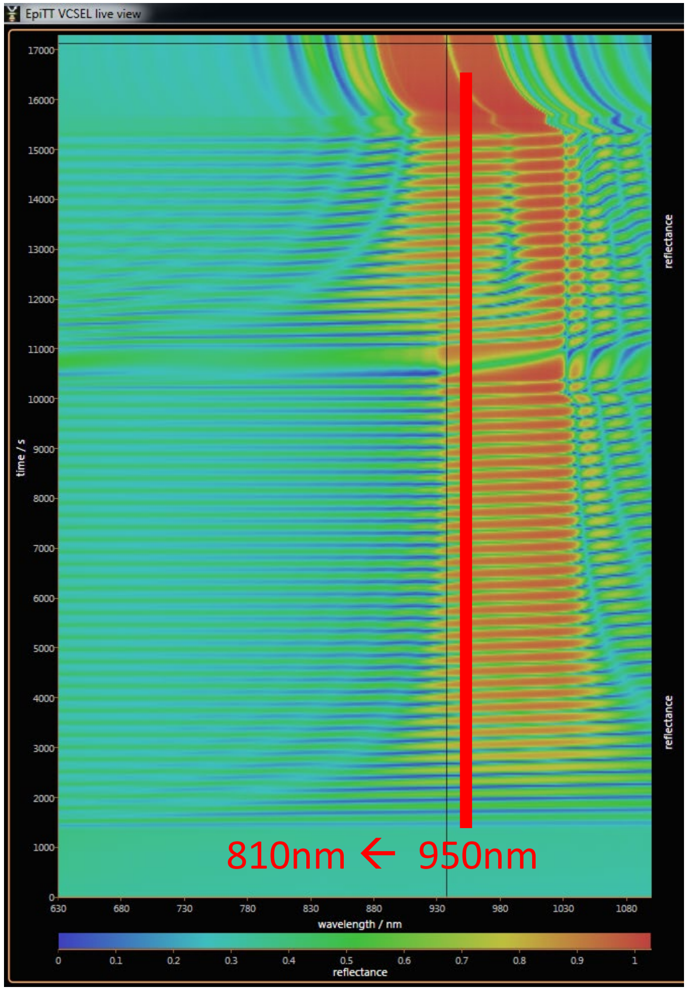
940nm VCSEL – adding a 2nd pyrometry wavelength



950nm pyro: wafer's thermal radiation blocked by DBR (ε=1-R <20%) → strong artifacts in T_{wafer}



Second 810nm pyrometer:
wafer's thermal emissivity ε always >60%
→ wafer temperature free of FPO artifacts



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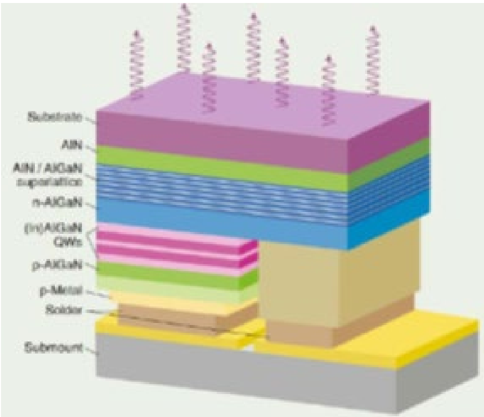
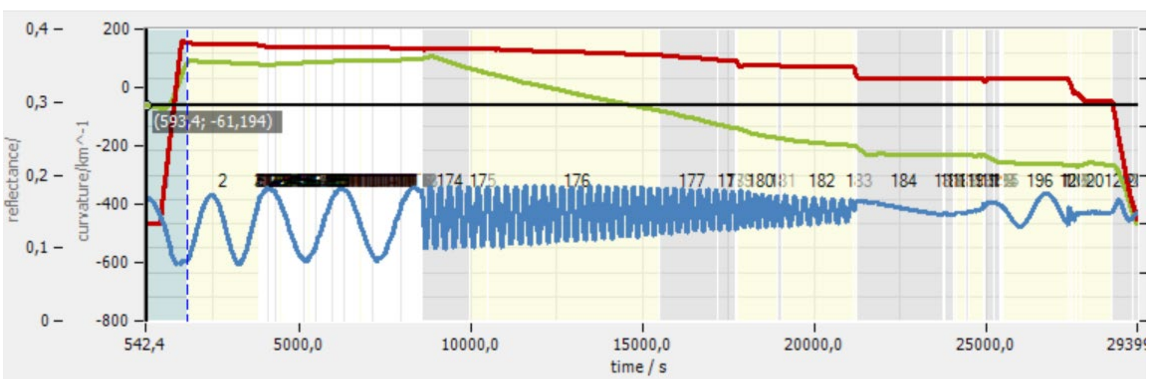
In-situ metrology for epitaxy of UV-C LEDs



- Growth on sapphire/AlN template
- 8h long epi; low growth rates for smoother interfaces
- two-step Epi:
  - template growth in AIXTRON G3
  - LED-structure in 6x2“ CCS
- Total thickness: 1.5µm AlN template + 5-6µm of LED
- 85 period GaN/AlN superlattice for defect reduction

4-wavelength reflectance monitoring (280/405/633/950nm) for providing access to all layer thicknesses



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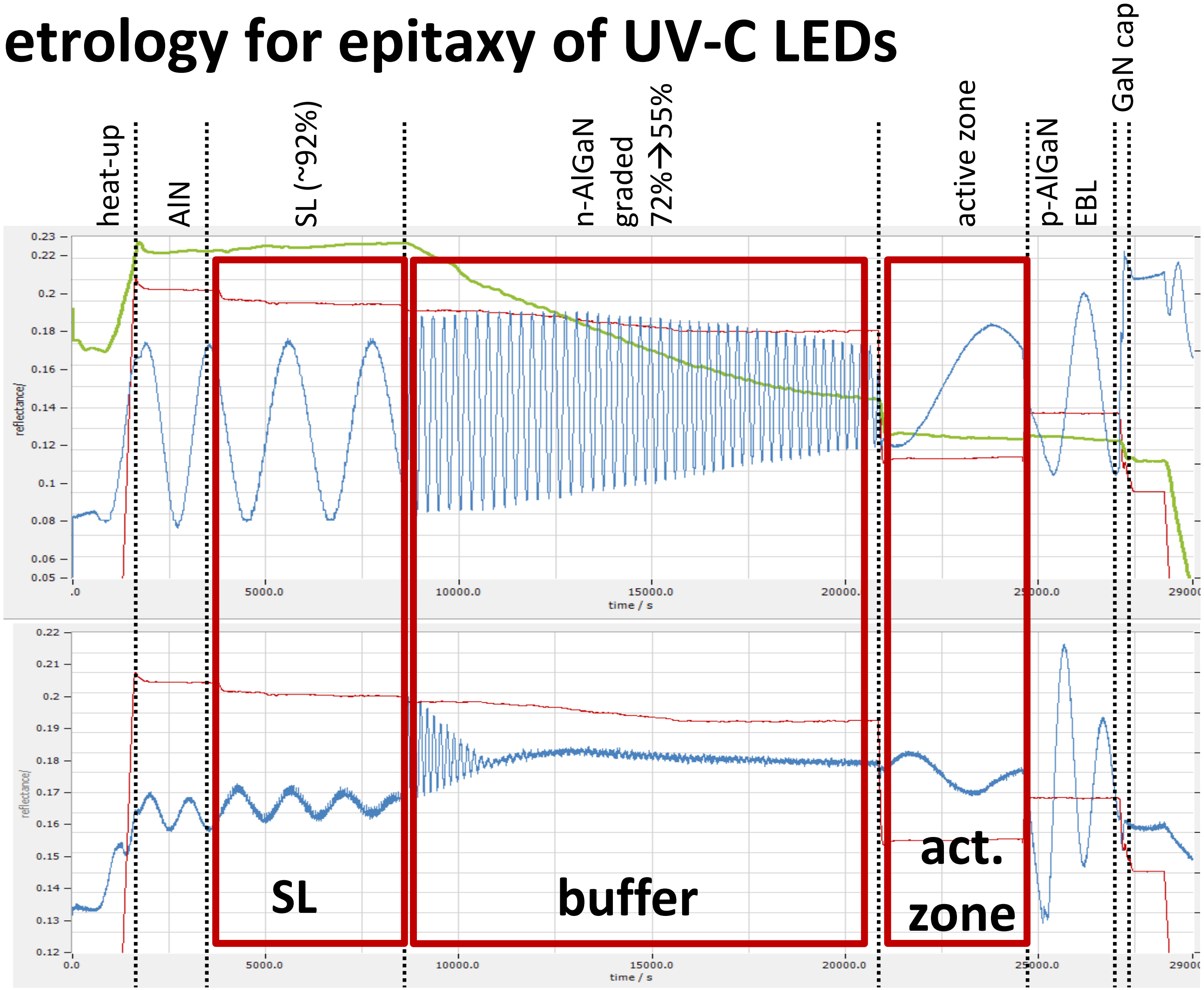
In-situ metrology for epitaxy of UV-C LEDs

R 405nm
curvature
temperature

R 280nm
curvature
temperature



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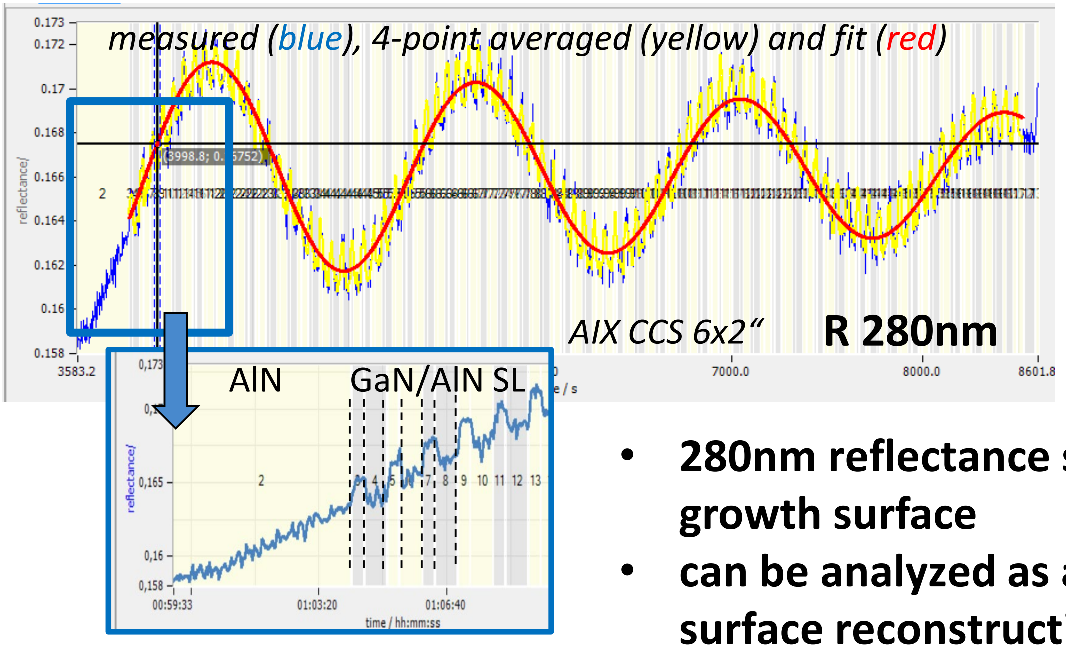
In-situ metrology for epitaxy of UV-C LEDs: Superlattice

- GaN/AlN SL is decisive at beginning of the UV LED epitaxy for defect reduction
- 85 periods, each single layer in the range of ~1nm



← fitting the 280nm reflection during SL growth yields SL total layer thickness of 201nm (red line)

- **280nm reflectance shows gas phase effects to the growth surface**
- **can be analyzed as a SPA experiment sensing the surface reconstruction changes from Al-rich → Ga-rich → Al-rich → ...**

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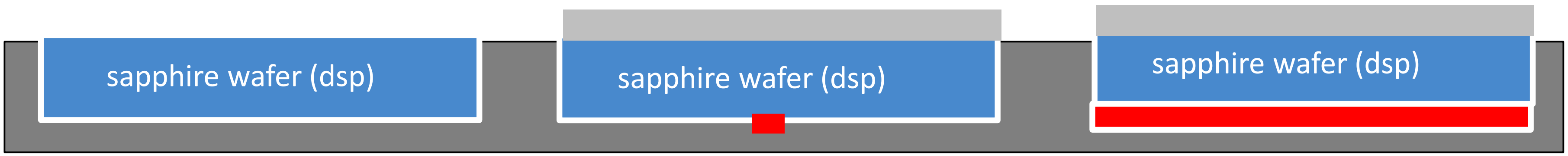
UV LEDs – so far no in-situ access to wafer temperature

- Fully NIR transparent substrates and layers do not allow pyrometry of wafer temperature - only pocket temperature measurement
- Molybdenum back-side coating is used for getting access to T_{wafer} of AlN/sapph templates at start of UV-LED process
- This is work in progress …



Wafer #1
bare sapphire (dsp)

Wafer #6
AlN/sapphire template
Mo marker (center back-side)

Wafer #4
AlN/sapphire template
Mo back-side coated

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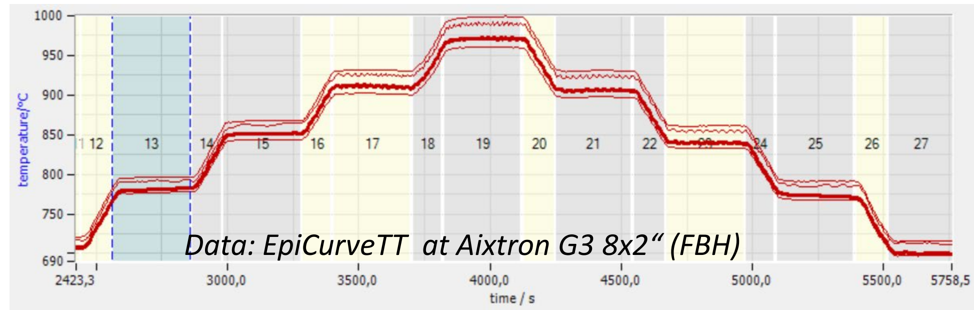
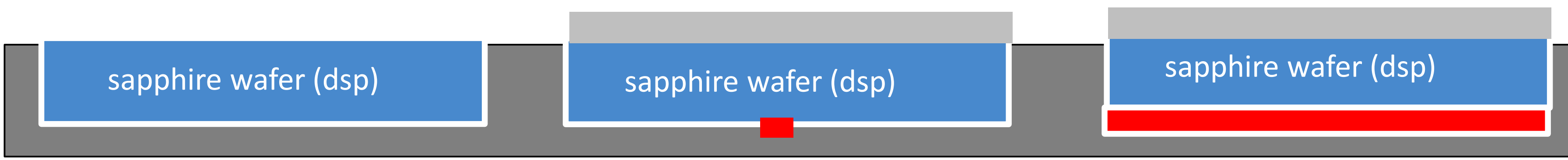
UV LEDs – so far no in-situ access to wafer temperature

- Heating run with three different wafers
- In-situ temperature measurement
- Approach will help studying wafer temperature during UV-LED epi





Wafer #1
bare sapphire (dsp)
T_{pocket} = 998°C

Wafer #6
AlN/sapphire template
Mo marker (center back-side)
T_{wafer} = 985°C

Wafer #4
AlN/sapphire template
Mo back-side coated
T_{wafer} = 996°C

- **The AlN template wafer temperature at begin of UV-LED growth is 13K below pocket (graphite/SiC) temperature**
- **Full Mo coating of sapphire back-side improves the heat-transfer**

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Outline

In-situ metrology for MOCVD – a brief sketch of historical development

Current metrology challenges

State-of-the-art metrology for VCSEL/DBR/SESAM

UV-LEDs: in-situ metrology for high Al-containing III-Ns

Summary and outlook

Summary and Outlook

- We have developed new methods and procedures for measuring the growth rates of thin layers in highly complex device structures
- high-yield manufacturing of current cutting-edge devices can only be facilitated by close integration of in-situ metrology into the MOCVD tools
- Grading of ternary layers in DBR-like structures can be analyzed in-situ
- Ex-situ mapping of Epi uniformity achieves a new level of accuracy by feeding in the results of in-situ analysis
- Feed-forward control schemes allow endpoint detection for DBR and cavity
- Precision in in-situ reflection gives access now to surface reconstruction changes during growth
- Challenges in wafer temperature sensing for VCSELs processes have been solved
- Wafer temperature in UV LED epi remains an open issue

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