

Advances and new trends in in-situ and connected metrology

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LayTec AG



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Outline

Introduction

UV LED: layer thickness and roughness

UV-LED: compositional grading

InP-laser: connected metrology

Summary and Conclusion

Outline

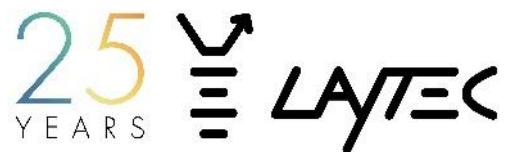
Introduction

UV LED: layer thickness and roughness

UV-LED: compositional grading

InP-laser: connected metrology

Summary and Conclusion



Optical Metrology Company founded 1999 in Berlin

- › 25+ years old
- › Spin-off of TU Berlin
- › 70 employees
- › ~4000 systems sold

- › Operating worldwide
- › Member of Nynomic 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



Optical metrology along the semiconductor manufacturing chain

costs



value



risks



high costs

high value
generation

temperature
thickness
composition

maintain or
destroy value

unknown
uniformity

wrong
etch stop

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

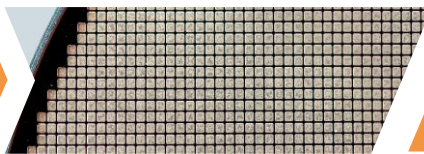
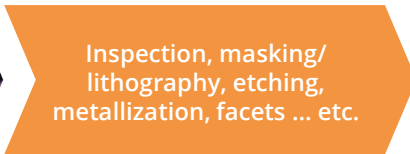
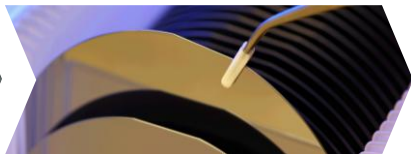
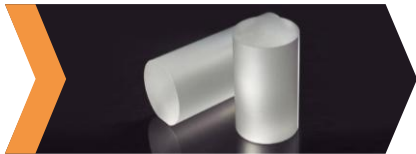
Substrate

Front-end
Level 0 - Epitaxy

Epi-wafer

Front-end
Level 1 - Dry Etching

Dies-on-wafer



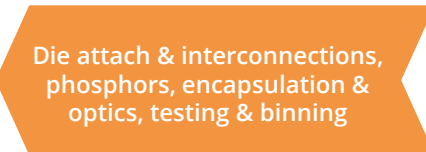
Inspection, masking/
lithography, etching,
metallization, facets ... etc.



systems & applications



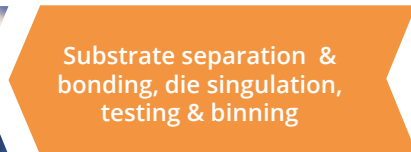
Packaged device



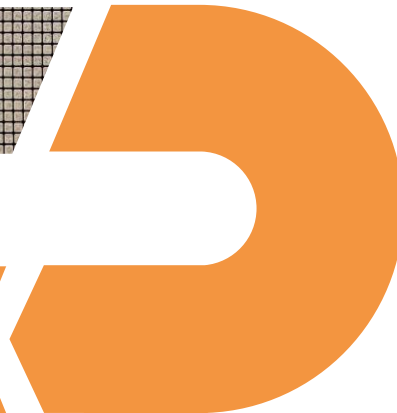
Back-end
Level 1 - Packaging



dies



Back-end
Level 0 - Packaging



Optical metrology along the semiconductor manufacturing chain



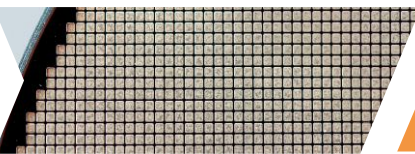
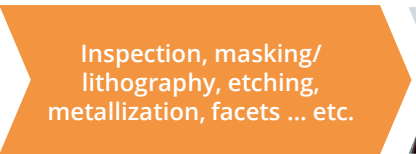
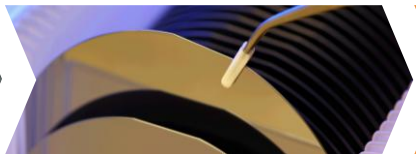
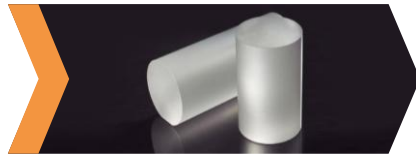
Substrate

Front-end
Level 0 - Epitaxy

Epi-wafer

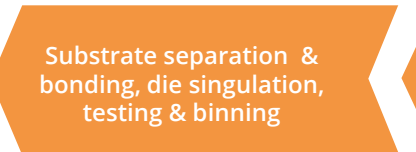
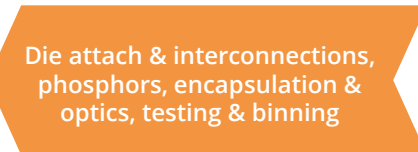
Front-end
Level 1 – Dry Etching

Dies-on-wafer



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

You'd better do the epi right...



systems & applications

Packaged device

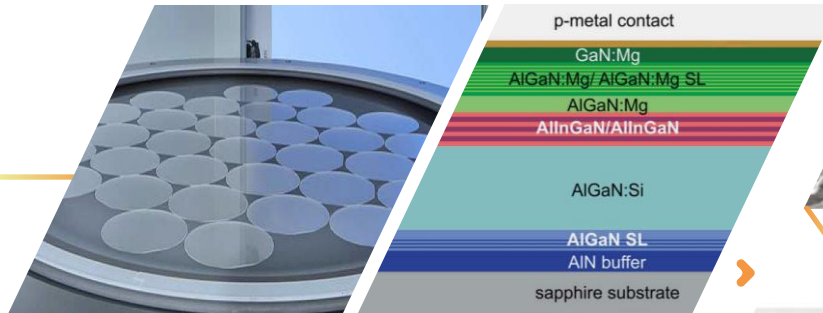
Back-end
Level 1 – Packaging

dies

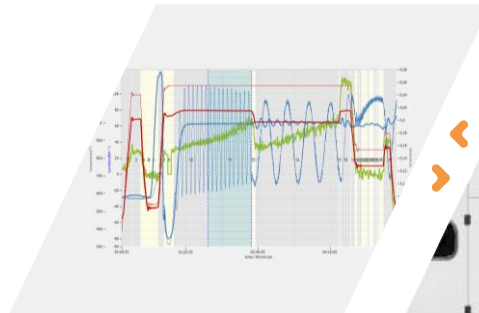
Back-end
Level 0 – Packaging

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



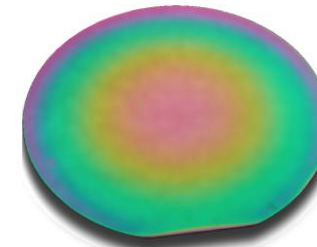
Optical techniques

- Pyrometry
- Reflectometry
- Deflectometry

MOCVD equipment

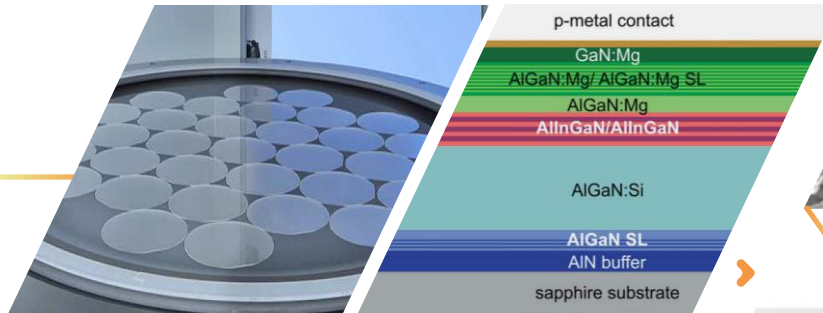


Characterized epi wafer

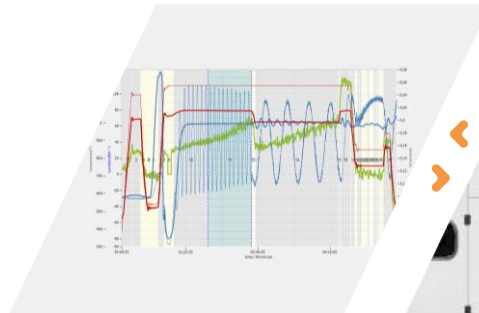


In-situ metrology for compound semiconductor epitaxy

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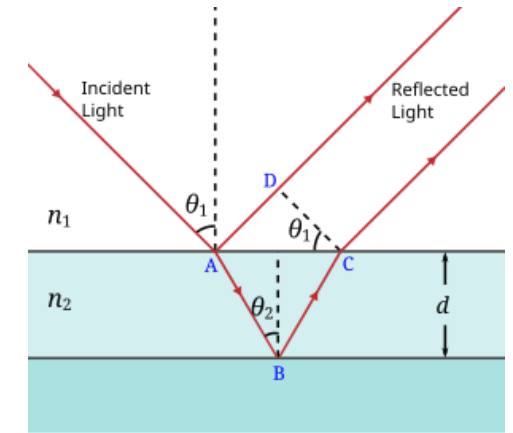
Optical in-situ metrology tool



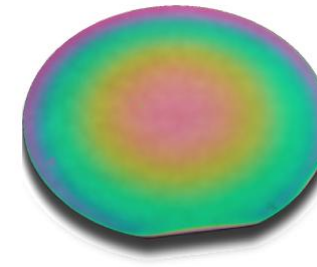
MOCVD equipment



Thin film interference

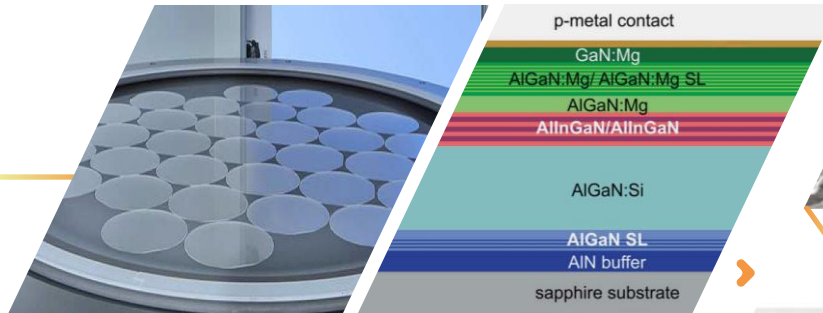


Characterized epi wafer

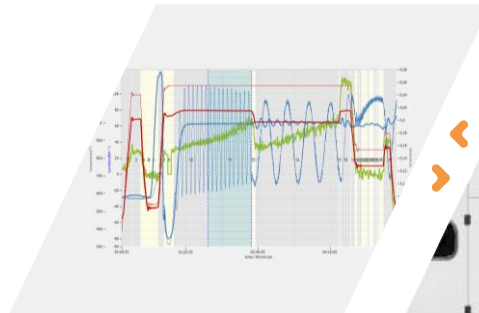


In-situ metrology for compound semiconductor epitaxy

Substrate wafers + recipe for layer stack



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Optical in-situ metrology tool

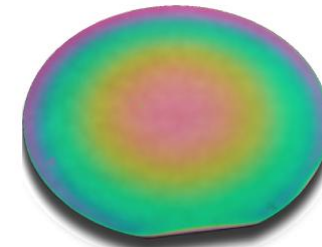


MOCVD equipment

Measurement of

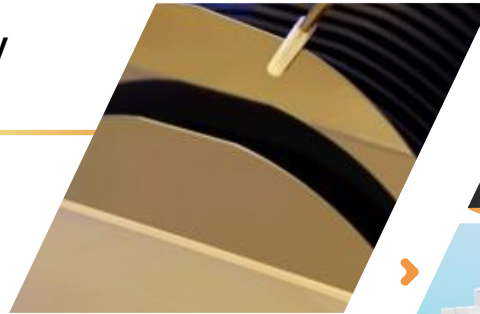
- › wafer temperature
- › growth rate
- › layer thickness
- › wafer curvature/bow
- › ternary composition
- › surface morphology
- › on-wafer uniformity
- › ...

Characterized epi wafer

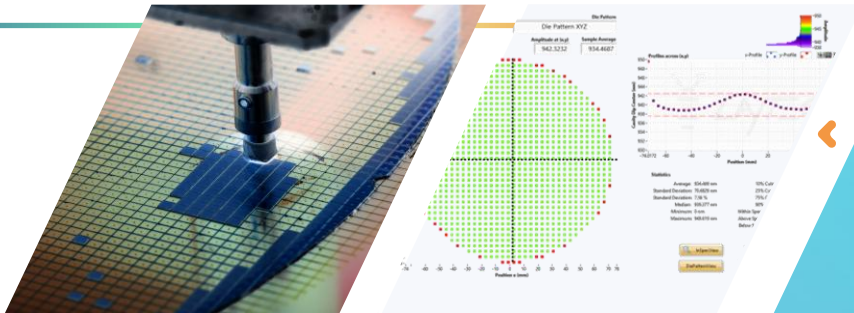


Post epi Metrology stations for complex layer stack wafer mapping – EpiX

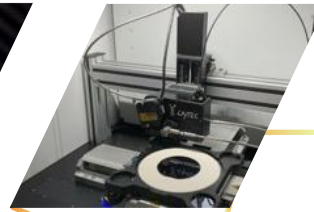
Single wafer mapping for uniformity analysis



Spatial, spectral and trace analysis for post-process quality of key parameters



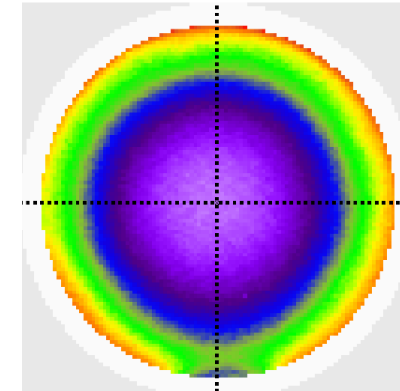
Automated xy-mapping



Measurement of

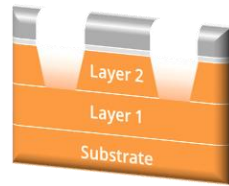
- White light reflectance (UV/vis/NIR)
- Photoluminescence
- Layer thickness
- Uniformity
- PL peak fit
- VCSEL analysis

Full uniformity information

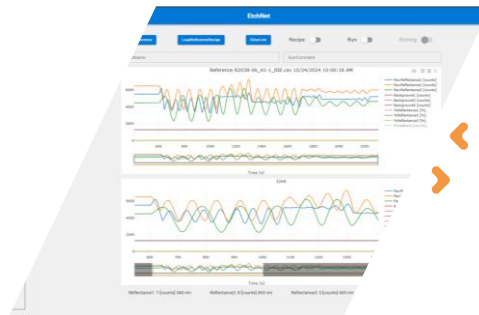


In-situ metrology for dry etching processes

End point detection during dry etching processes



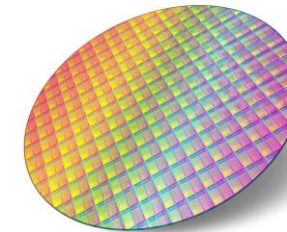
In-situ data for process control = monitoring and control of key etching parameters



Optical in-situ metrology tool



Plasma etch equipment



In-spec etched wafer

Multi wavelength measurement of

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

LayTec "Metrology Ecosystem"

EpiCurveTT:

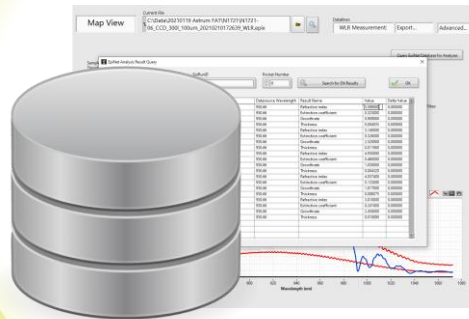
in-situ measured layer thickness
and other layer properties



In-situ metrology
during MOCVD

Connected Metrology

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



Outline

Introduction

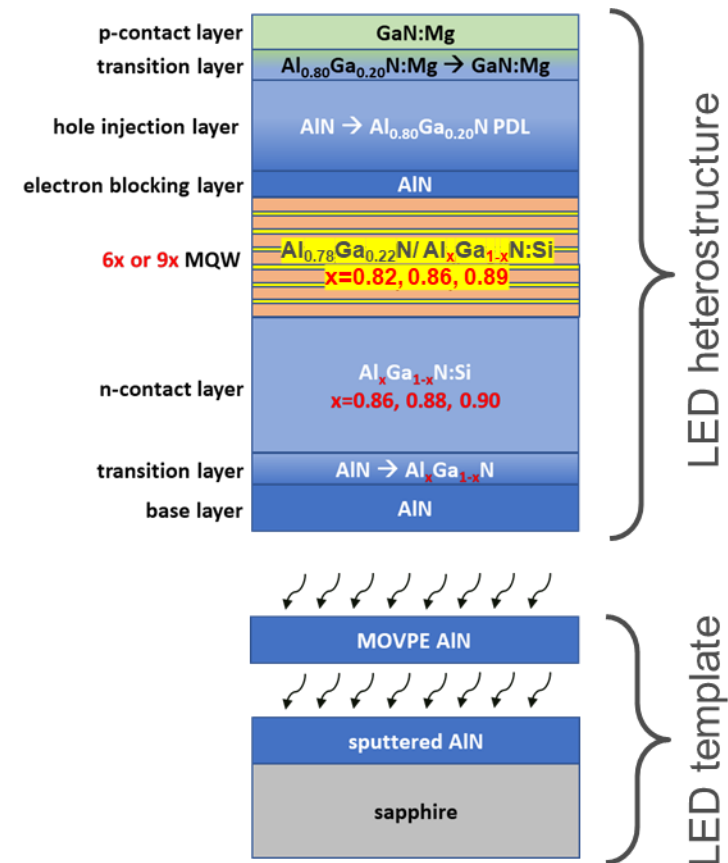
UV LED: layer thickness and roughness

UV-LED: compositional grading

InP- laser: connected metrology

Summary and Conclusion

Growth of far-UVC LEDs: Heterostructure and Equipment



TDD: $2\text{--}4 \text{ E}8 \text{ cm}^{-2}$

↘ = high temperature annealing (HTA)

9×2" sputtering system



11×2" high temperature planetary reactor



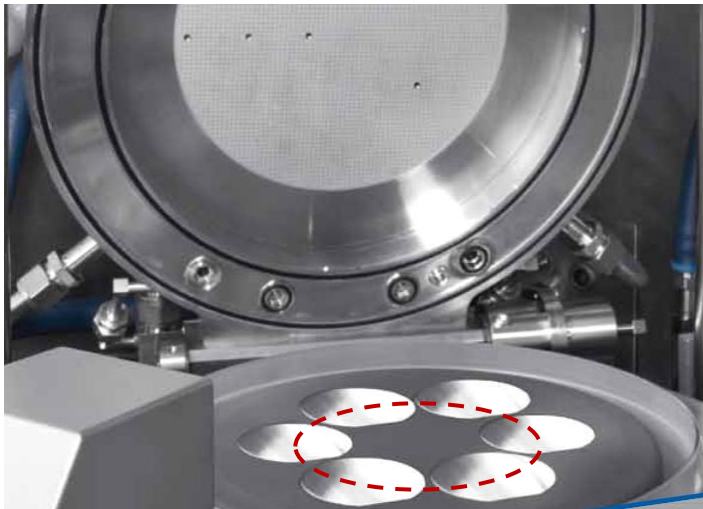
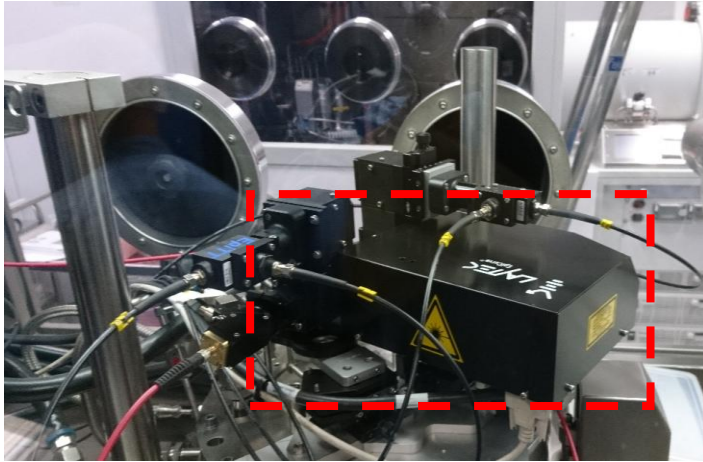
16×2" high temperature oven



6×2" close coupled showerhead reactor



Optical in-situ metrology during MOCVD – how does it work?

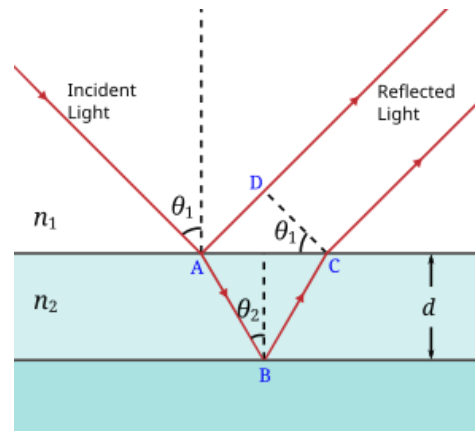


Pyrometry at 950nm (and 400nm) → temperature

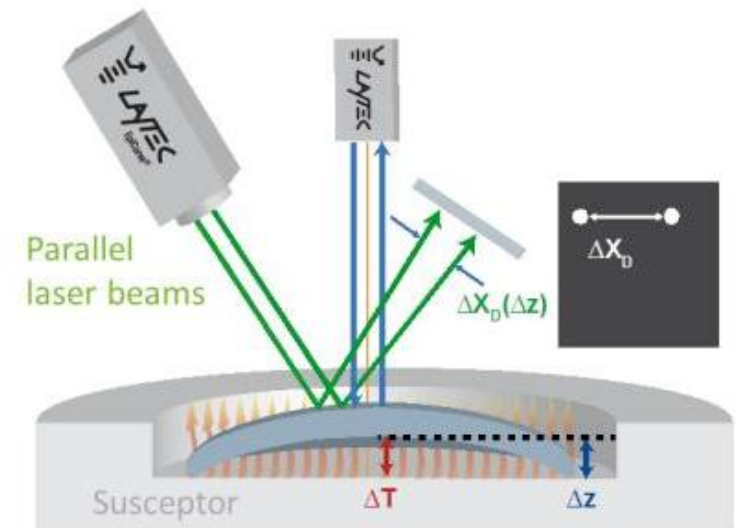
Reflectometry at 280nm, 365nm, 405nm, 633nm, 950nm → thickness

Deflectometry → wafer curvature (incl. asphericity detection)

Thin film interference



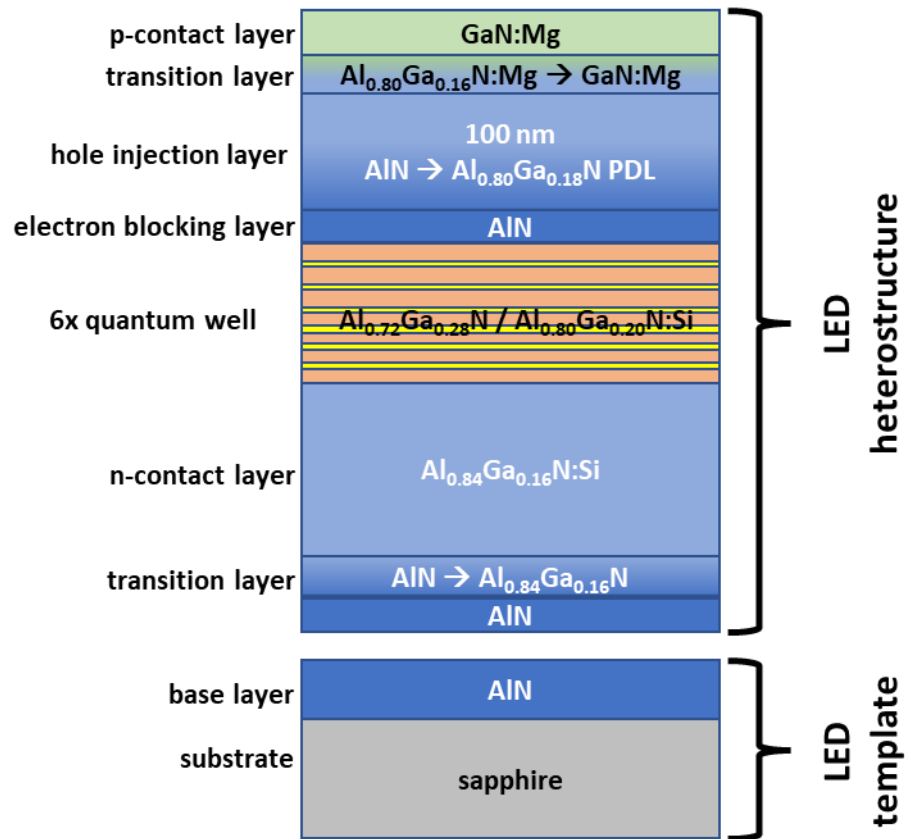
Fabry-Pérot-Oscillations



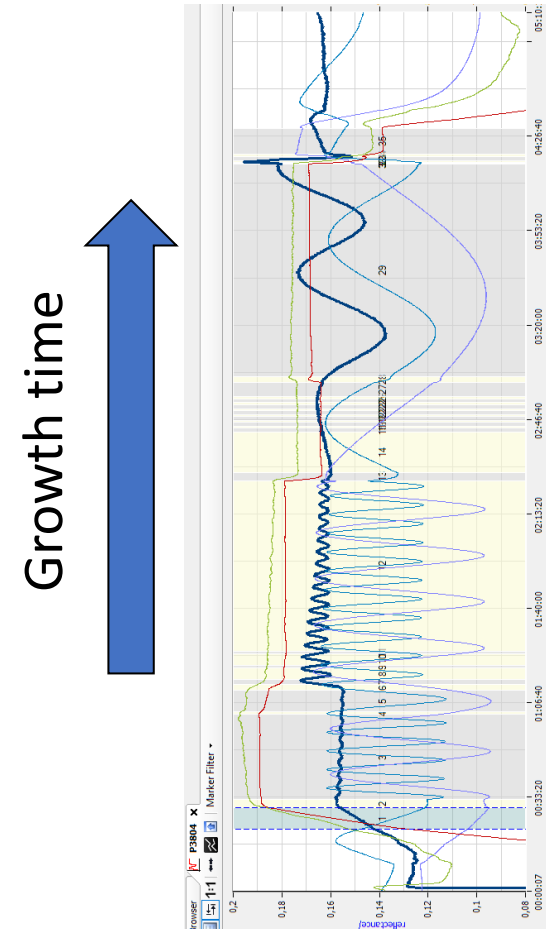
Curvature

Optical in-situ metrology for MOCVD of UV-LED structures

Schematic layer stack of UV-LED



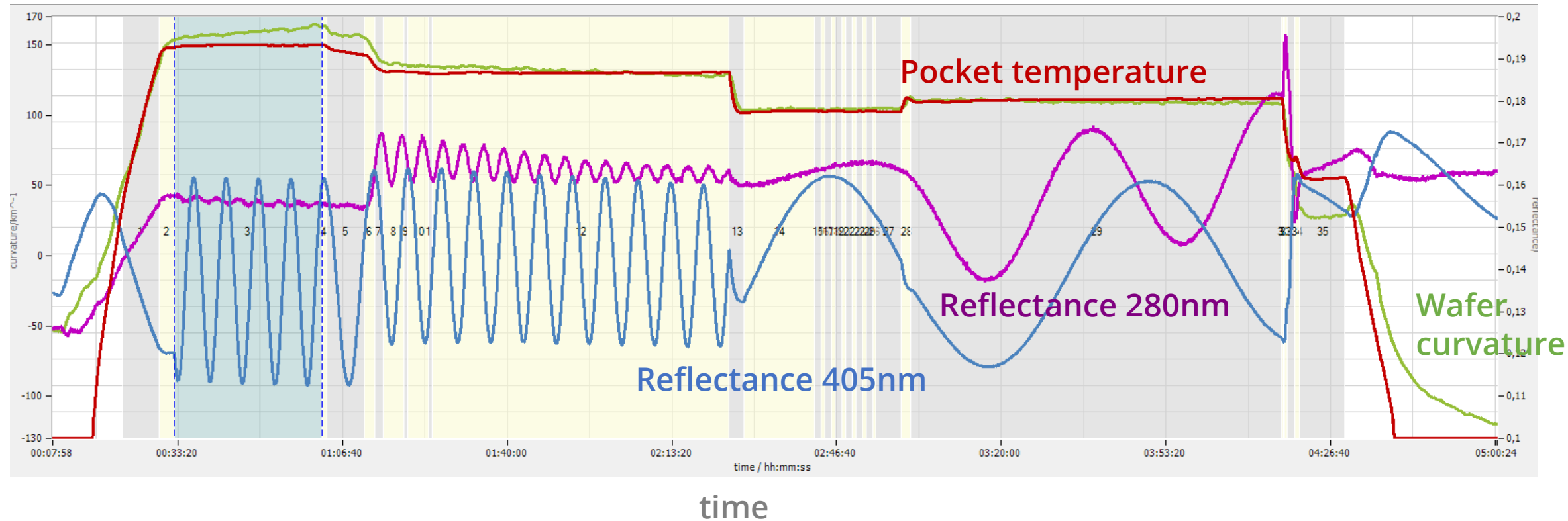
In-situ data



In-situ data of 230 nm UV LED

temperature, reflectance, curvature

heating | AlN Buffer | n-AlGaIn layer | active zone | AlGaIn pol. dop. layer | GaN | cooling

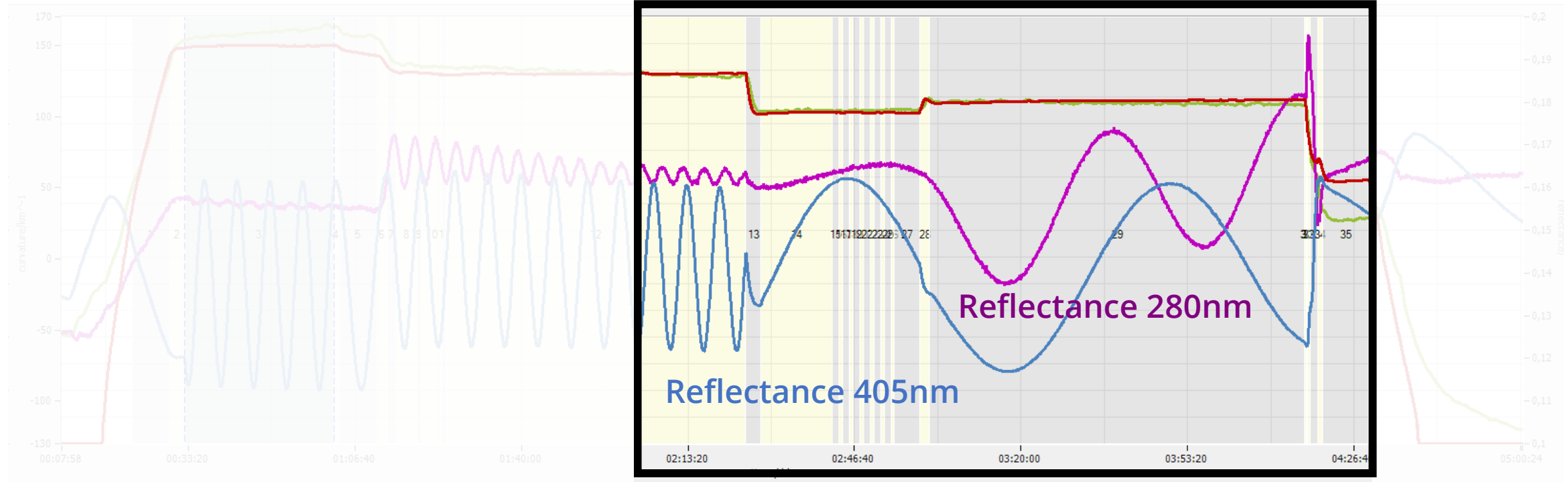


- In-situ data:
a treasure trove of information about each layer and each wafer

Quantitative analysis of layer properties

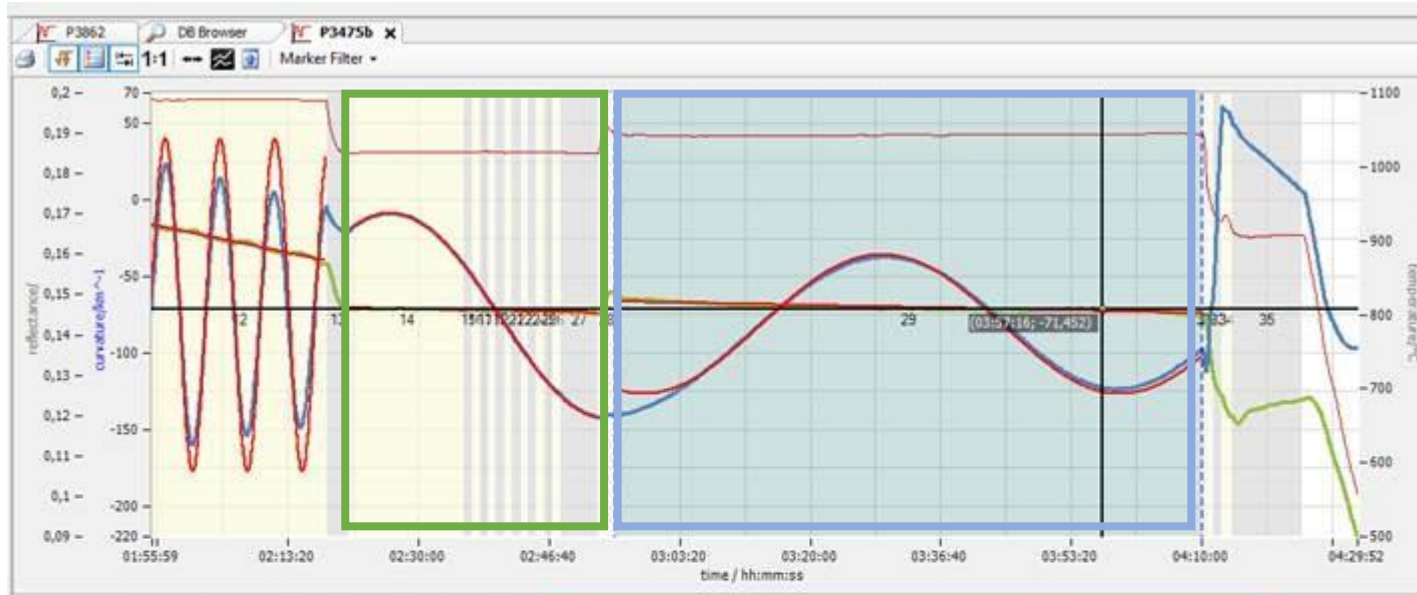
temperature, reflectance, curvature

heating | AlN Buffer | n-AlGaN layer | active zone | AlGaN pol. dop. layer | GaN | cooling



➤ Let's fit the reflectance based on a physical model

Analysis of in-situ measured reflectance



measured reflectance data
with process steps

active zone (complete)
thickness = 52nm

first MQW barrier
thickness = 24nm
last MQW barrier
thickness = 8nm

AlGaIn PDL layer
thickness = 110nm

Position	Step	Begin	End	Analysis Name	State	Result	Comment
1	3	1544,65	3343,44	Basic Slope	✓	Slope = -0.007 km ⁻¹ /s; Intercept = 82.927 km...	
2	3	1544,65	3343,44	Growthrate Fit with reflectance correction	✓	GR = 0.847 μm/h; D = 0.423 μm	
3	5	3403,28	3863,5	Basic Slope	✓	Slope = -0.019 km ⁻¹ /s; Intercept = 118.642 k...	
4	5	3403,28	3863,5	Growthrate Fit with reflectance correction	✓	GR = 0.554 μm/h; D = 0.071 μm	
5	8-12	4083,2	8291,13	Basic Slope	✓	Slope = -0.018 km ⁻¹ /s; Intercept = 106.876 k...	
6	8-12	4083,2	8291,13	Growthrate Fit with reflectance correction	✓	GR = 0.777 μm/h; D = 0.908 μm	
7	14-27	8471,84	10377,4	Basic Slope	✓	Slope = -0.001 km ⁻¹ /s; Intercept = -57.937 k...	
8	14-27	8471,84	10377,4	Growthrate Fit with reflectance correction	✓	GR = 0.099 μm/h; D = 0.052 μm	
9	29	10501,27	15001,56	Basic Slope	✓	Slope = -0.002 km ⁻¹ /s; Intercept = -48.856 k...	
10	29	10501,27	15001,56	Growthrate Fit with reflectance correction	✓	GR = 0.088 μm/h; D = 0.110 μm	

analysis recipe
= layer stack + analysis functions

Cross-section STEM

Analytical STEM

Tecnai F20 twin (FEI)

- **FEG-Schottky Cathode**
20 keV - 200 keV
- **HAADF-Detector**
Fischione model 3000
- **CCD-TEM-Detector**
Gatan Orius 600
- **EELS / EFTEM system**
GIF Quantum™ SE 200kV

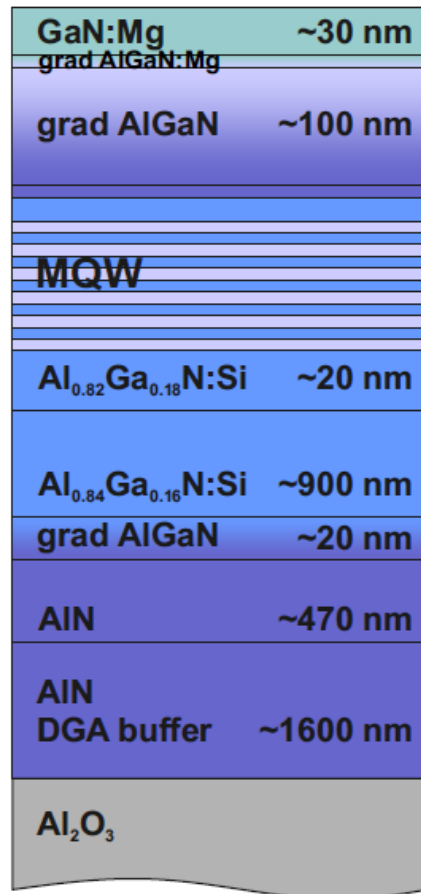


MonoCL4 (Gatan)

- **liquid helium single tilt, (x, y, z)**
TEM-cryo-sample holder
- **retractable parabolic mirror**
(x,y, z adjustable)
- **GaAs (Cs) photomultiplier**
R934-02
- **CCD CL parallel detector**
for CL spectral imaging

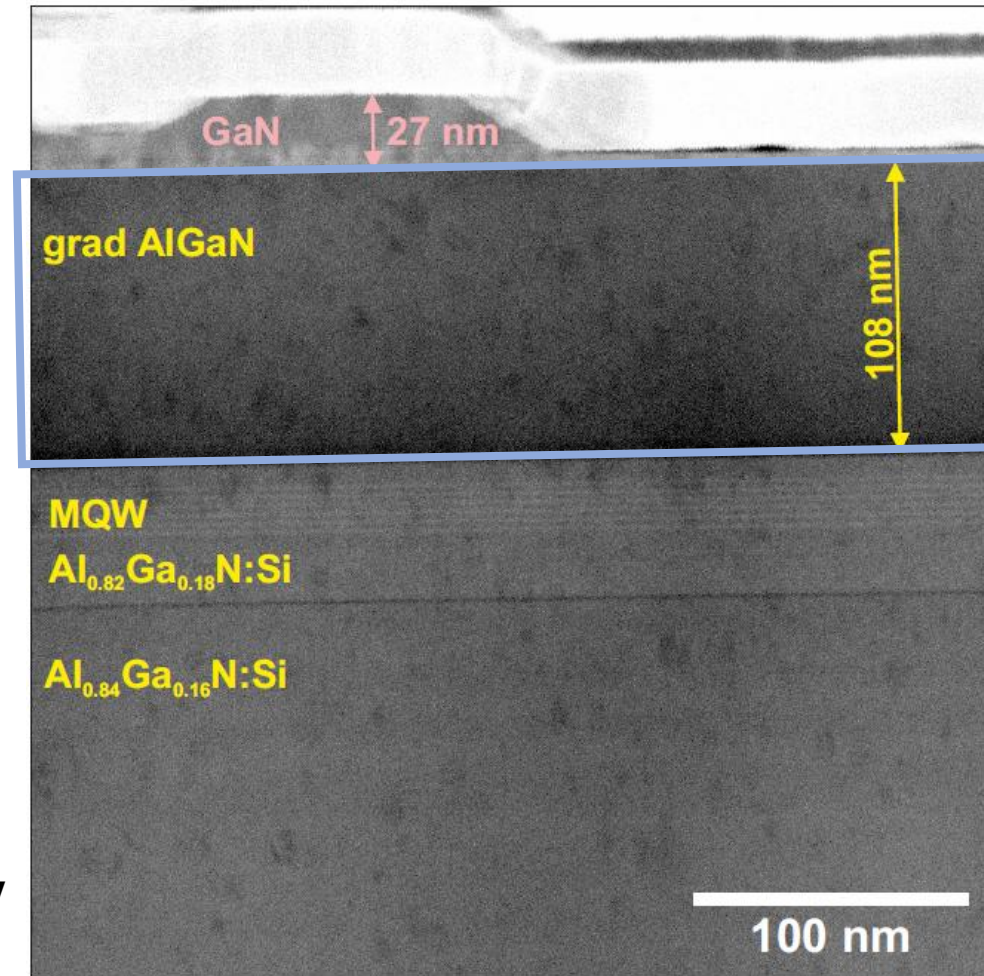
Cross-section STEM PDL

deep UV LED



not to scale

STEM (HAADF)

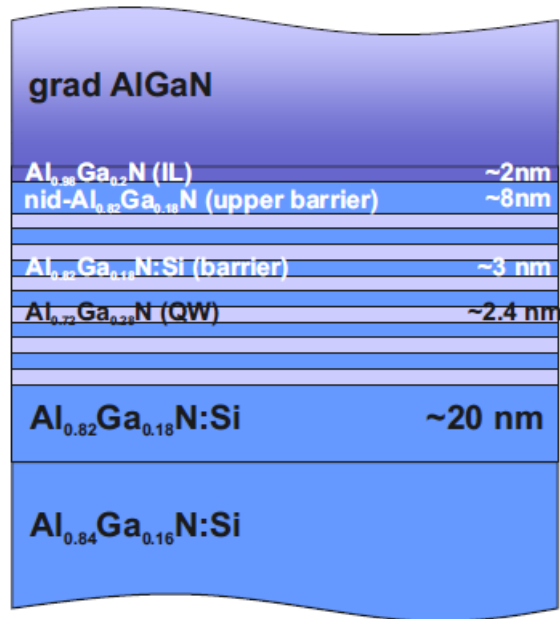


80 keV
5-12 K



Cross-section STEM active zone

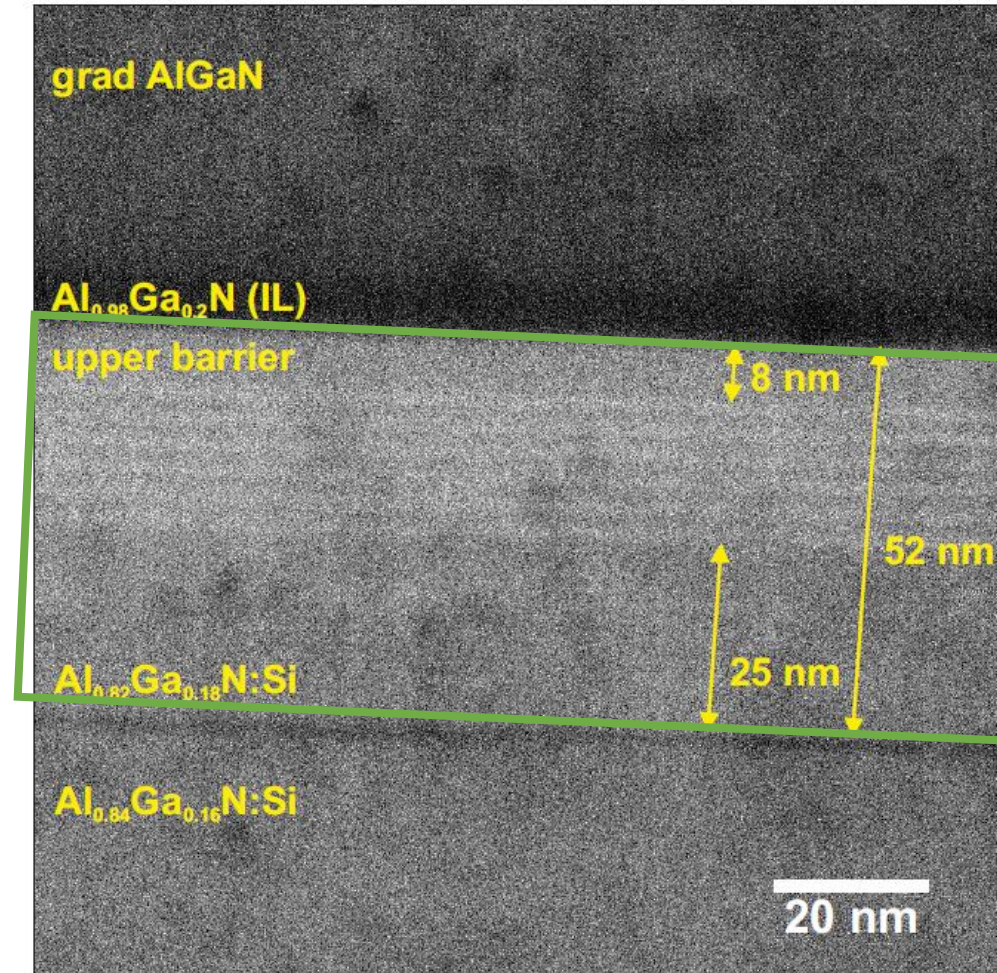
deep UV LED:
active region



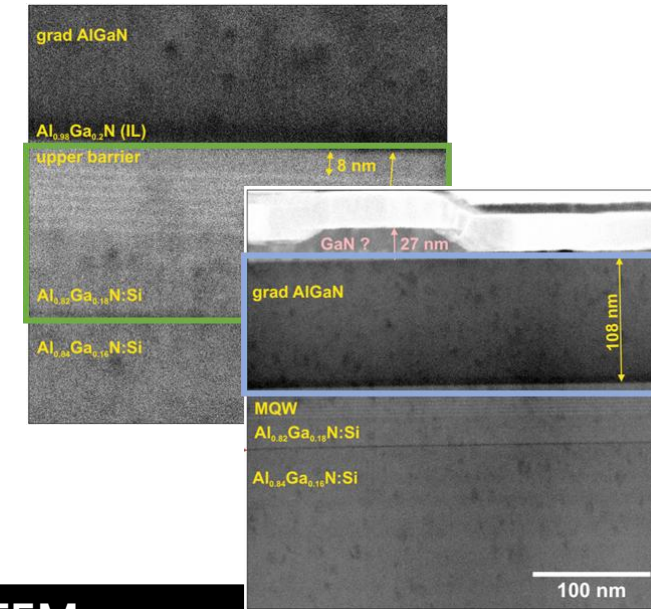
not to scale

80 keV
5-12 K

STEM (HAADF)



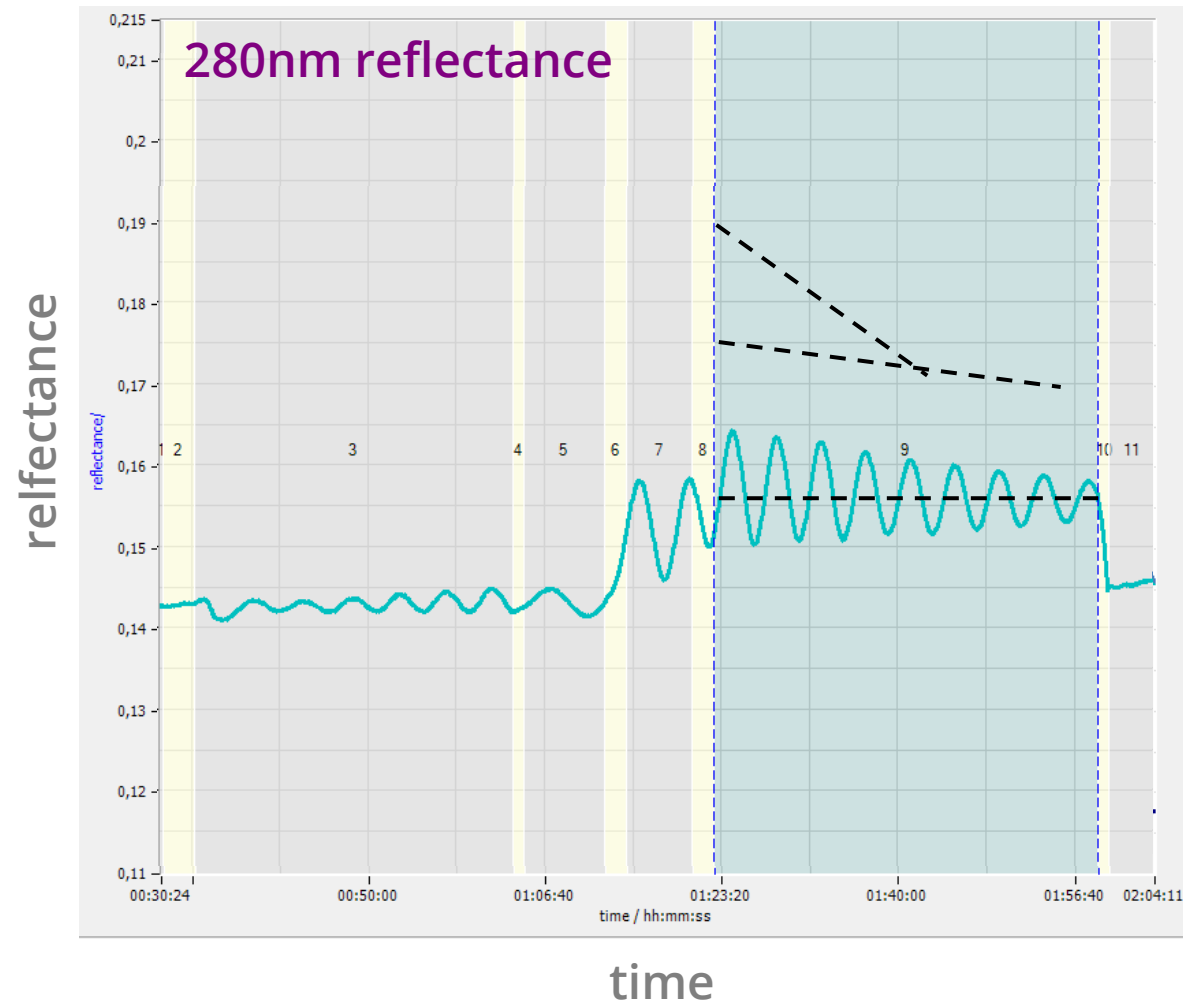
Comparison between in-situ and STEM



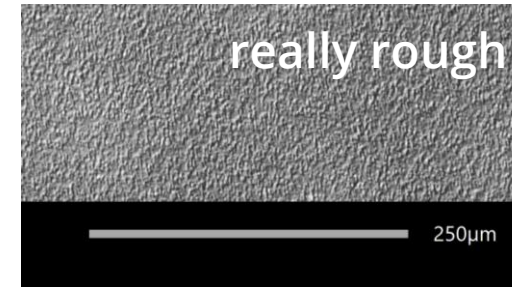
Layer	In-situ	STEM
Active zone (complete)	52 nm	52 nm
First barrier	24 nm	25 nm
Last barrier	8 nm	8 nm
AlGa _{0.18} N PDL	110 nm	108 nm

➤ excellent agreement within 2nm

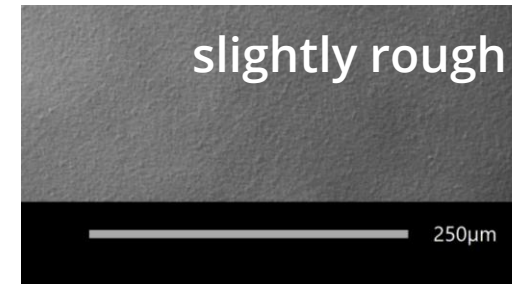
Characterization of surface roughness: ~300 nm thick AlGaN layer



AlGaN 60%



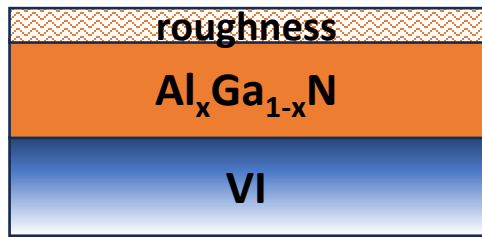
AlGaN 70%



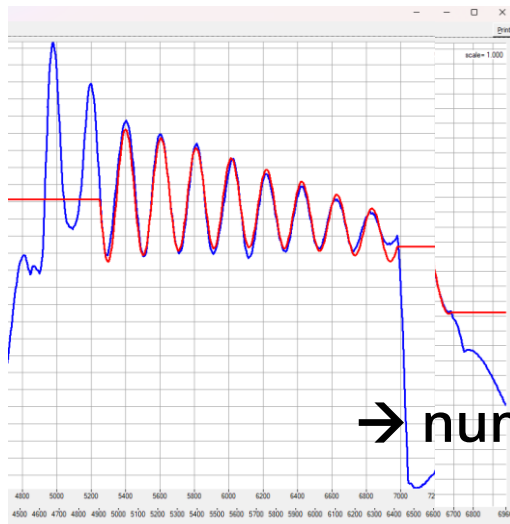
AlGaN 80%



Characterization of surface roughness: quantitative modelling

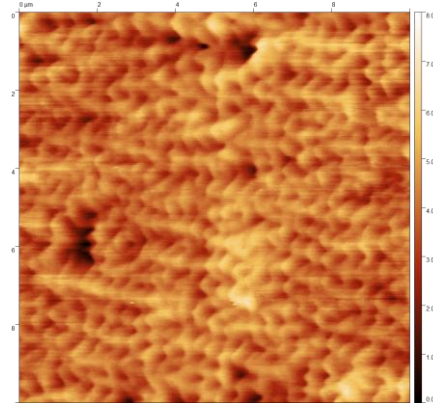

 d_{EMA}

VI virtual interface
EMA effective medium layer



→ number are not direct comparable, but correlate well

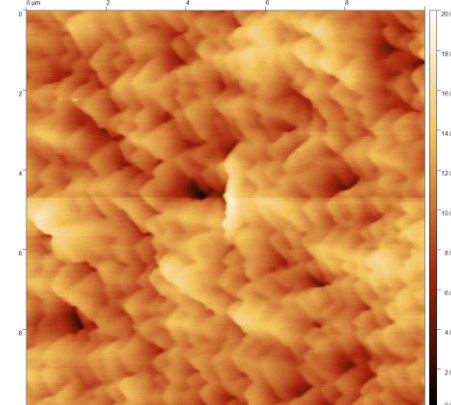
AlGaIn 80%



$$\sigma_{\text{rms}} = 0.8 \text{ nm}$$

$$d_{\text{EMA}} = 1.82 \text{ nm}$$

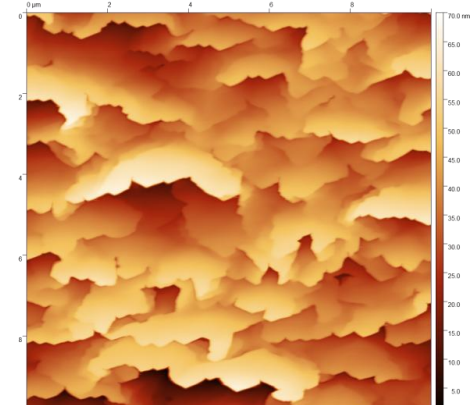
AlGaIn 70%



$$\sigma_{\text{rms}} = 2 \text{ nm}$$

$$d_{\text{EMA}} = 4.7 \text{ nm}$$

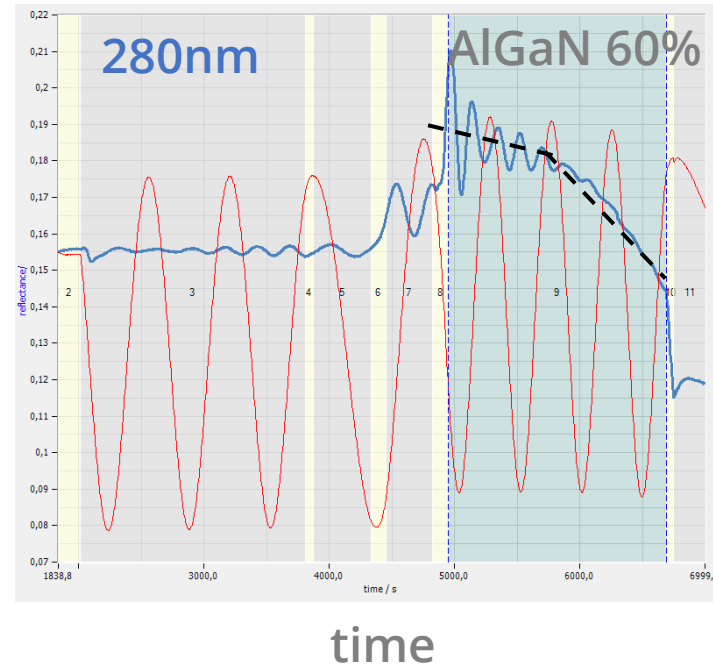
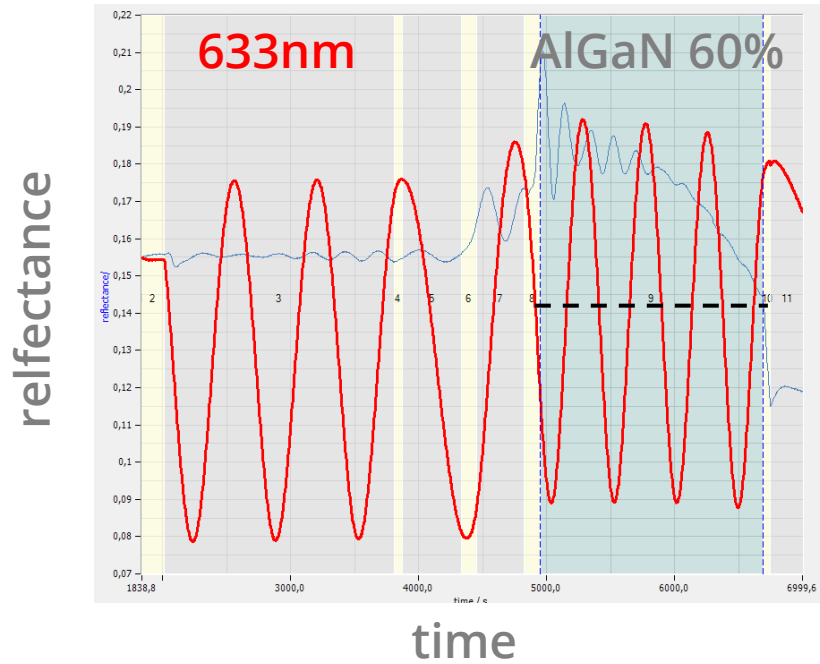
AlGaIn 60%



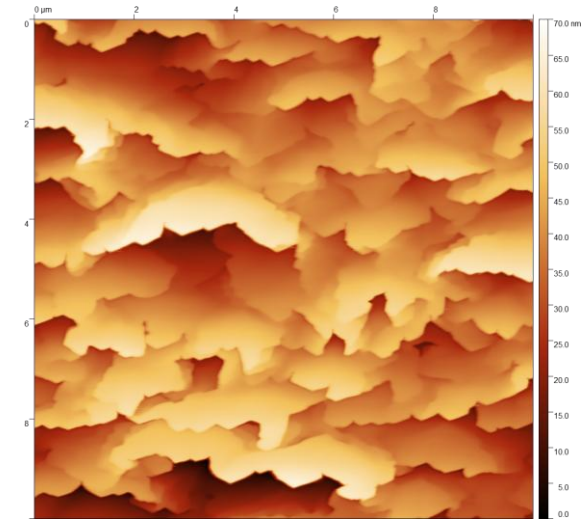
$$\sigma_{\text{rms}} = 10.4 \text{ nm}$$

$$d_{\text{EMA}} = 14.6 \text{ nm}$$

Benefit of 280nm reflectance



AFM $\sigma_{\text{rms}} = 10.4 \text{ nm}$



- Long wavelength (633nm) is not sensitive to roughness
- Short wavelength (280nm) is much more sensitive to surface roughness (decrease in reflectance)

Outline

Introduction

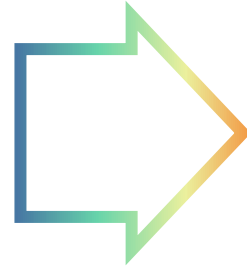
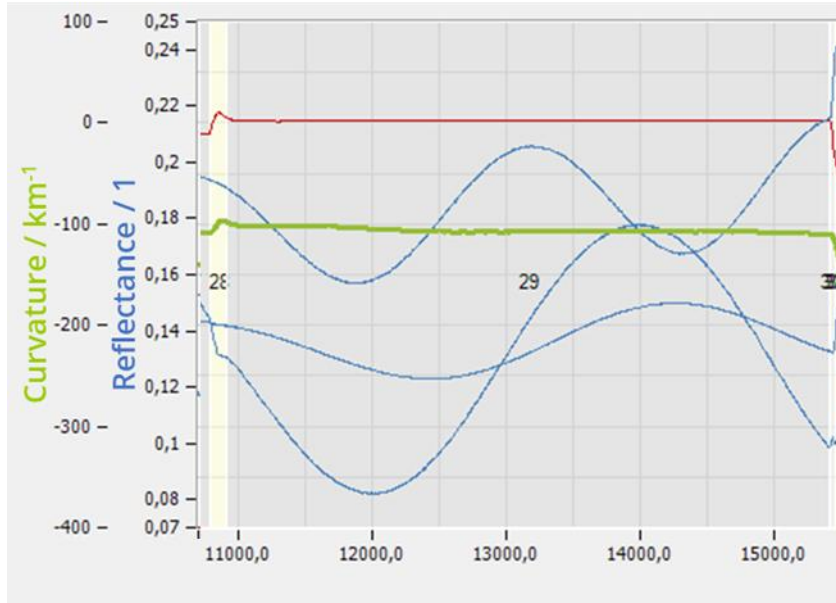
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UV-LED: compositional grading

InP- laser: connected metrology

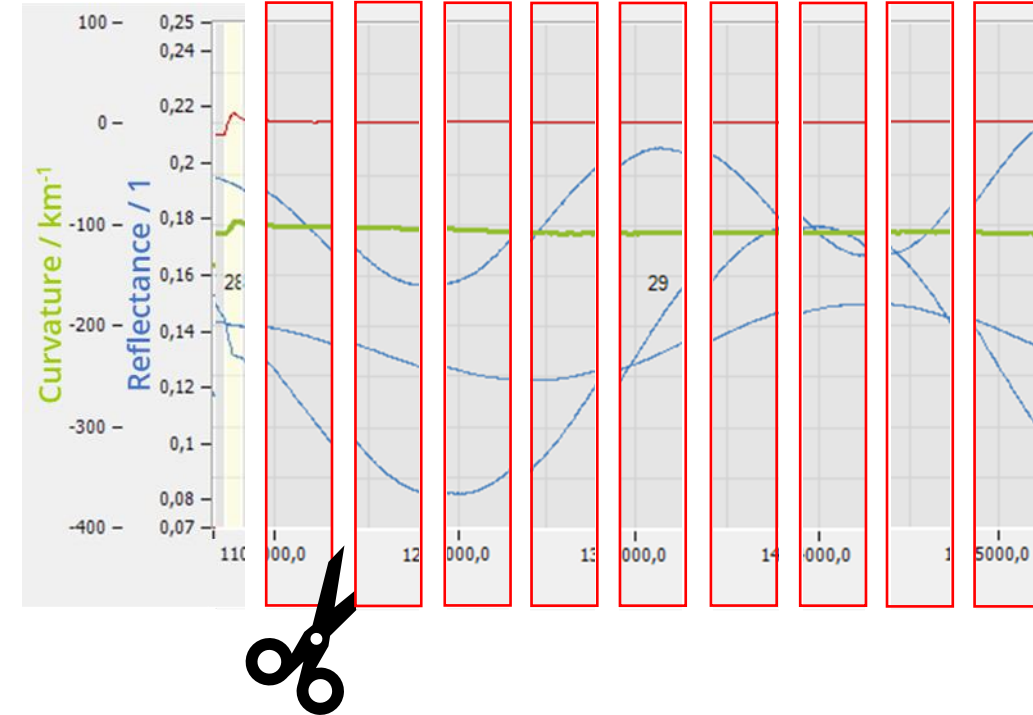
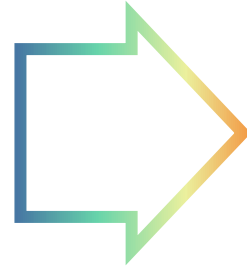
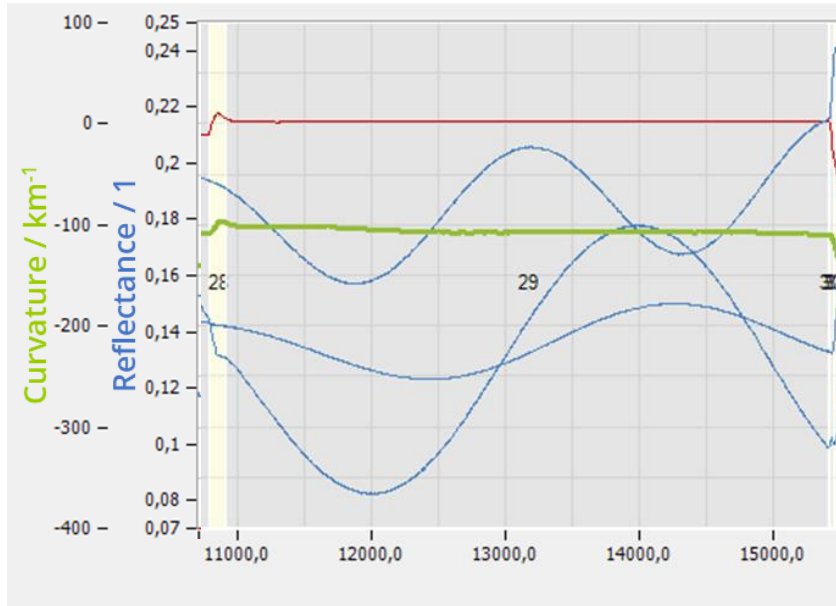
Summary and Conclusion

How to analyze composition grading in polarization doping layer?



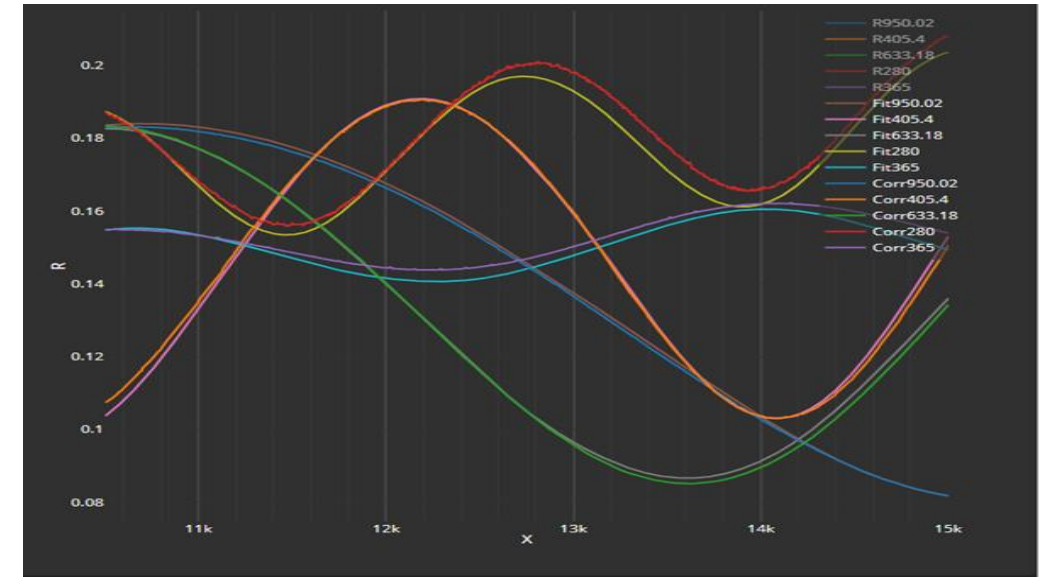
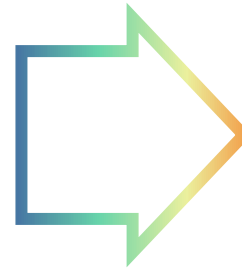
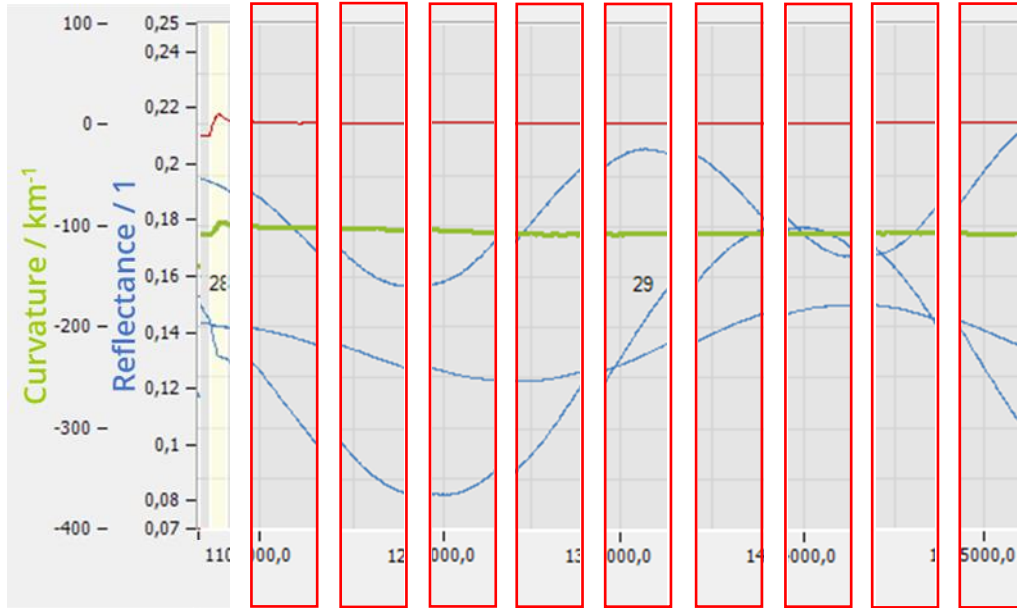
- ~100nm thick hole injection layer with intentional grading of composition
- Grading goal is AlN $\rightarrow$ $\text{Al}_{0.8}\text{Ga}_{0.2}\text{N}$
- Intentional grading is realized by ramping of precursor concentration
- To date, no in-situ monitoring and ex-situ verification of the exact gradient is possible

Our approach for composition analysis



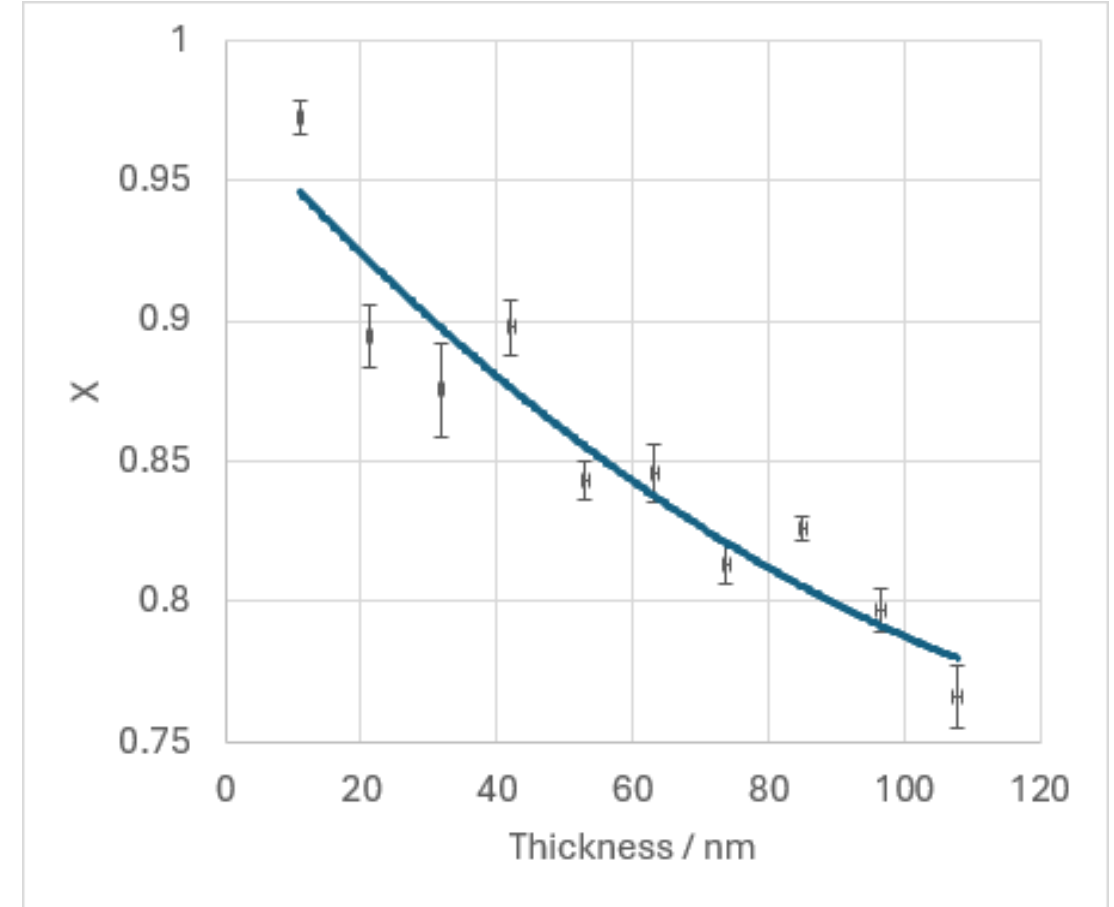
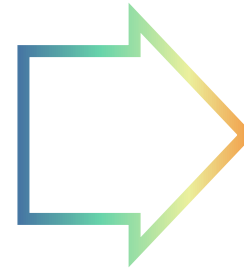
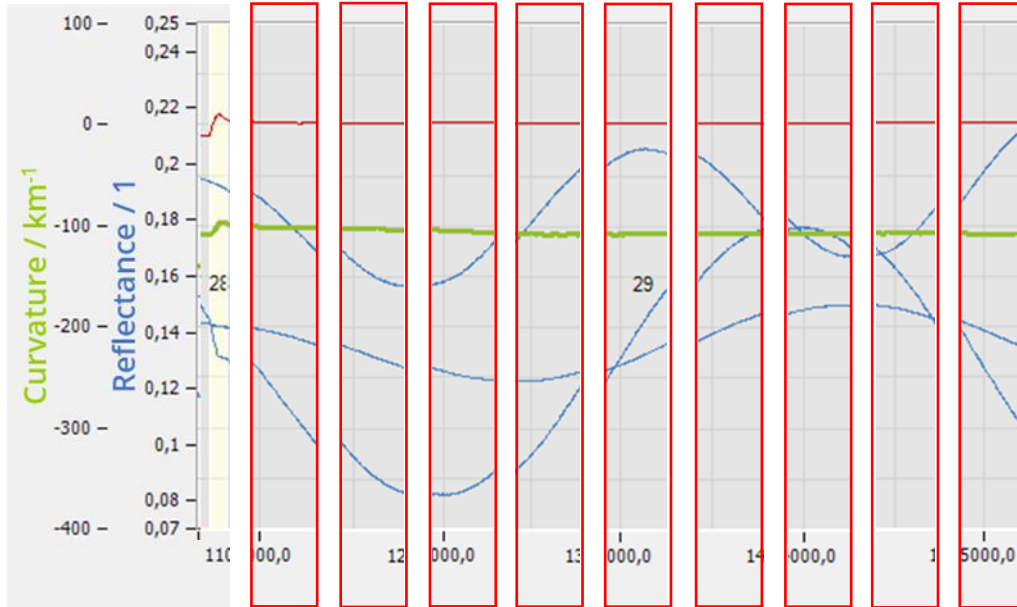
- Separation of process step in an appropriate number of “sub-step slices”
- Analysis of each single sub-step slice by LayTec’s multi-wavelengths composition fit
- Applied to shortest available wavelengths (280nm/365nm/405nm) for maximum sensitivity

Simulating and fitting compositional grading



- For each Sub-step slice individual growth rates and composition values are obtained by applying a *Multi-WL Composition Fit*
- Fitting is fully automated within EpiNet Analytics
- Very good agreement of measured and modelled curves

In-situ monitoring of far-UV-C LED MOVPE growth



- Result is AlGaIn composition profile
- In good agreement with expectation
- Benchmarking by SIMS is planned

Outline

Introduction

UV LED: layer thickness and roughness

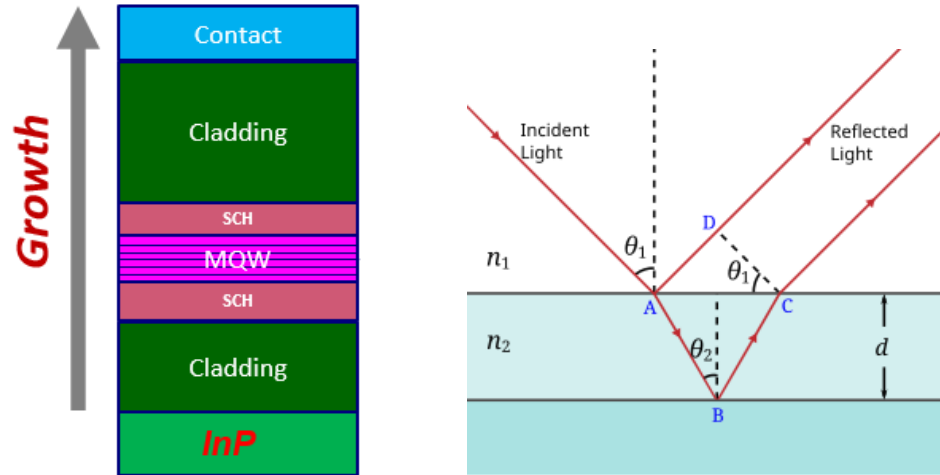
UV-LED: compositional grading

InP- laser: connected metrology

Summary and Conclusion

Growth and etching of InP-based laser structures

Schematic layer stack

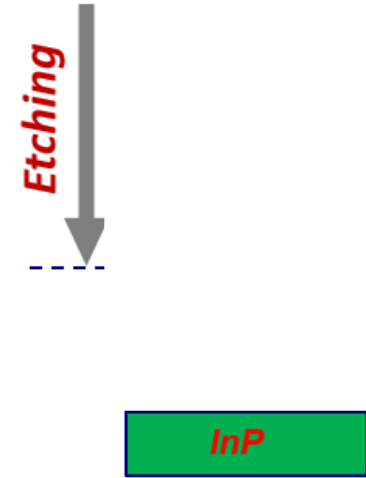


In-situ metrology during epitaxy

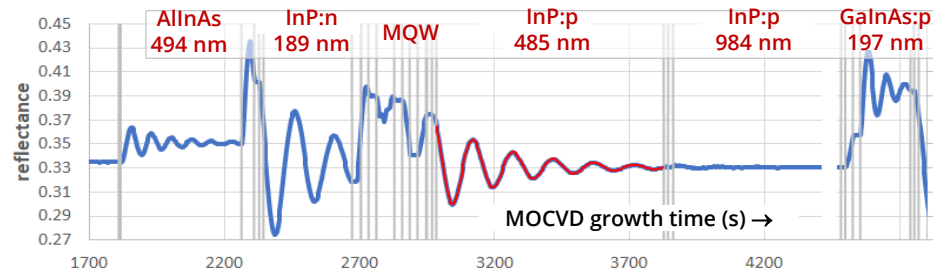
- Measure growth rate and layer thickness
- Interface detection by communication with epi tool
- Thickness information can be used for controlling etching process

In-situ metrology during etching

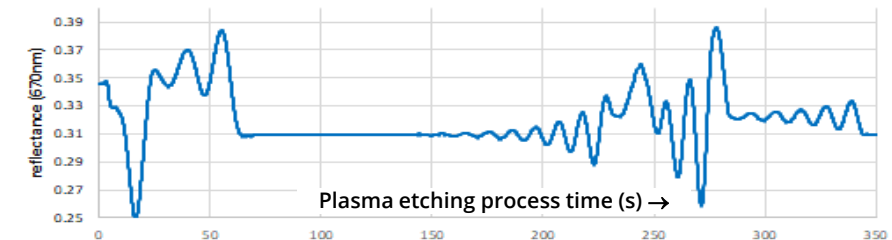
- Interfaces must be detected based on optical signal
- Etch rate can be measured
- Residual thickness can be calculated



Reflectance data during growth

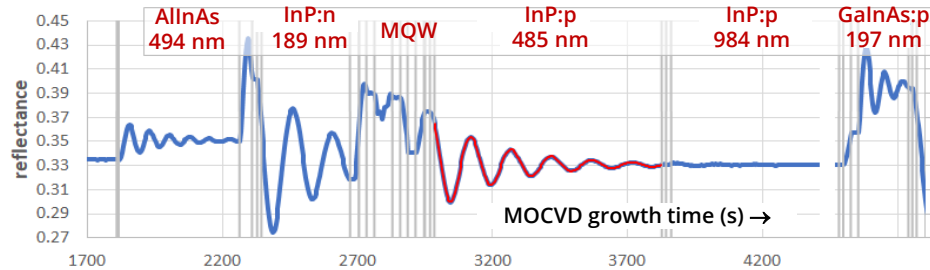


Reflectance data during etching



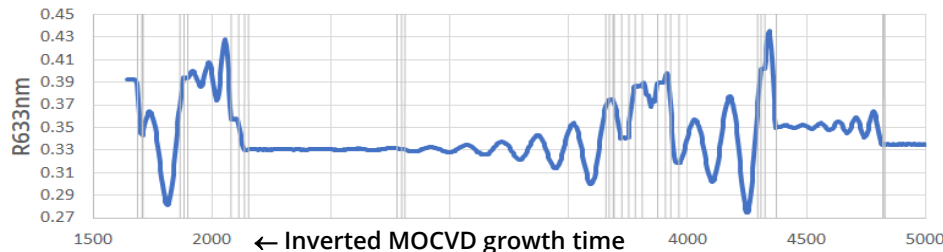
Connection between reflectance data from growth and etching

Reflectance data during growth



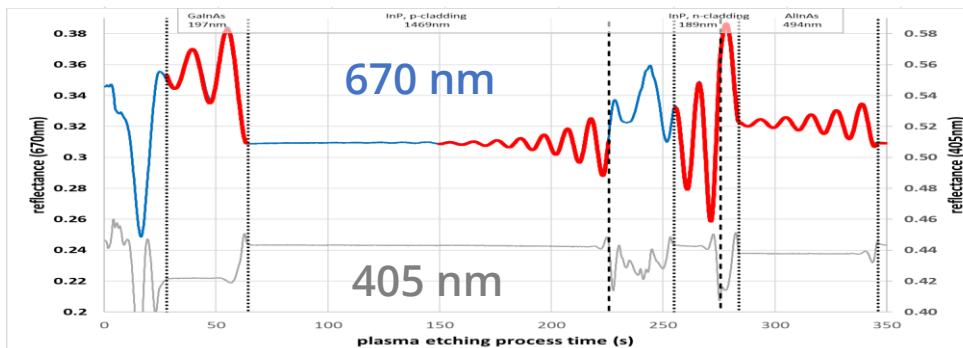
- › layer thickness measurements with accuracy in ± 1 nm range
- › Valve actions mark begin/end of layers
- › At epitaxy temperatures ($\sim 700^\circ\text{C}$)

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

Outline

Introduction

UV LED: layer thickness and roughness

UV-LED: compositional grading

InP- laser: connected metrology

Summary and Conclusion

Summary and Conclusion

- **In-situ metrology provides real-time access to important layer properties during MOVPE: temperature, reflectance, curvature**
 - In-situ reflectance measurements allow to determine growth rates and layer thickness with high accuracy
 - Layer thickness measured ex-situ with cross-section STEM is in full agreement with in-situ measured thickness ($\pm 1\text{nm}$)
 - UV wavelengths (e.g. 280nm) for reflectance measurements increase sensitivity for roughness determination substantially
 - Roughness “thickness” can be analyzed quantitatively and correlates well with AFM
 - Compositional grading in polarization doping layer can also be analyzed
- **In-situ reflectance monitoring during plasma etching allows precise endpointing**
 - In-situ data from Epi are providing a target dataset for plasma etch process control
 - Connected metrology is very valuable for yield improvement



Knowledge is key

www.laytec.de

