LayTec's in-situ and ex-situ metrology for VCSEL epitaxy

J. Beltran

LayTec AG, Berlin, Germany

as presented at LayTec in-situ seminar (satellite workshop to EWMOVPE 2019, Vilnius)

LAYTEC
Knowledge is key

LayTec EPIX – for 2D mapping of III-V epi wafers

- LayTec metrology tools for in-situ and ex-situ analysis of VCSEL wafers
  - VCSEL Add-On to EpiTT and EpiCurve® TT
  - LayTec EPIX – for 2D mapping of III-V epi wafers
- Synergizing in-situ and ex-situ metrology for fully understanding your samples and optimizing your growth process
- LayTec EPIX 2D mapping station
  - Optimizations for industry customers – faster 2D analysis through data interpolation
  - Application options for Academia – multiple upgrade options and custom software interfaces

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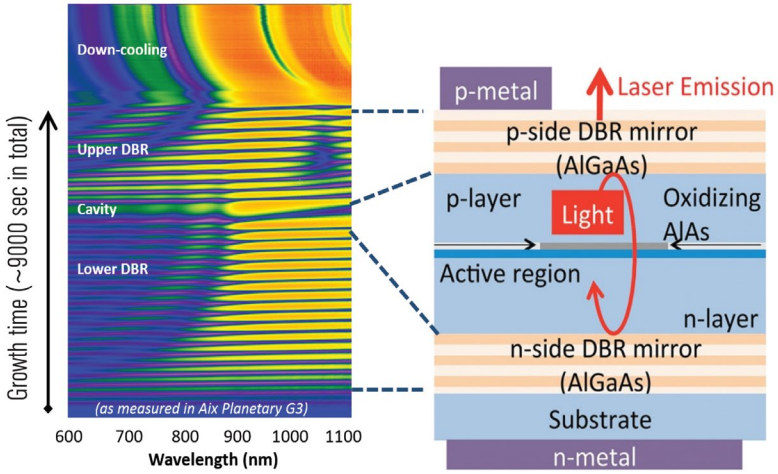
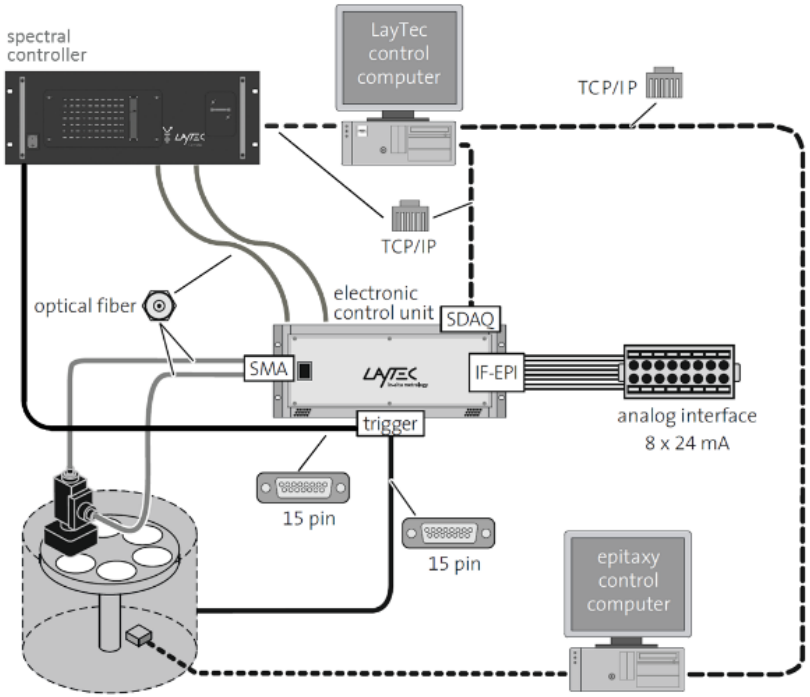
VCSEL Add-On to EpiTT and EpiCurve® TT

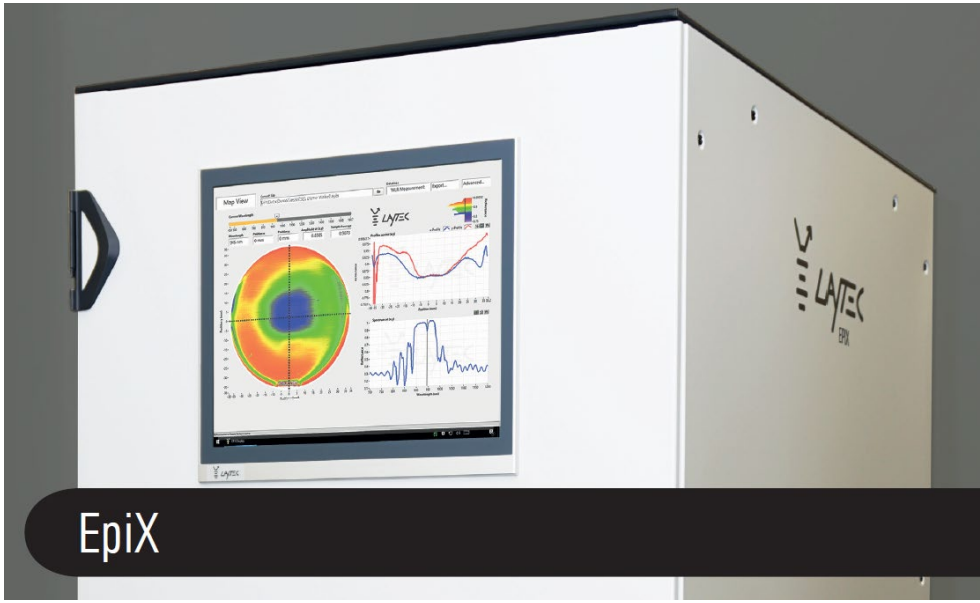




- Normalized reflectance measurements in the full spectral range (630 nm - 1100 nm)
- Time resolved spectroscopic measurement mode (color plot mode)
- Automated detection of VCSEL optical parameters (cavity dip, stop-band position) at growth temperature and correlation with room-temperature

LayTec EPIX – for 2D mapping of III-V epi wafers

Measurements	white light reflectance (WLR) photoluminescence (PL)
Sample size	up to 200 mm
Spectral range	400-1700 nm
Scan speed	up to 30 spectra/s



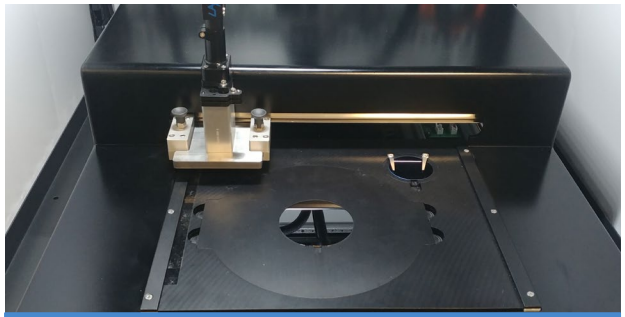
- Automatic determination of wafer center and diameter with accuracy ≤ 3µm
- Recipe-based measurements and automated analyses
- samples statistics and pass / fail classification on wafer-level and die-level
- multiple upgrade options (more optical heads, extended wavelength range, software interfaces)

Knowledge is key

LayTec EPIX – for 2D mapping of III-V epi wafers

LayTec EPIX system

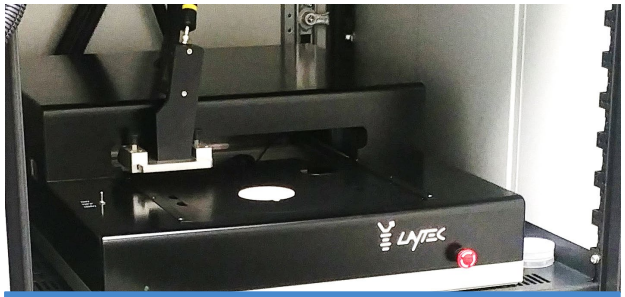
White light reflectance measurements using LayTec EpiTT VCSEL hardware



Mapping stage with 3" sample holder plate

PL measurements using LayTec PEARL hardware

(in-line PL monitoring system, sold since 2011)



PL measurement head

LAYTEC Knowledge is key

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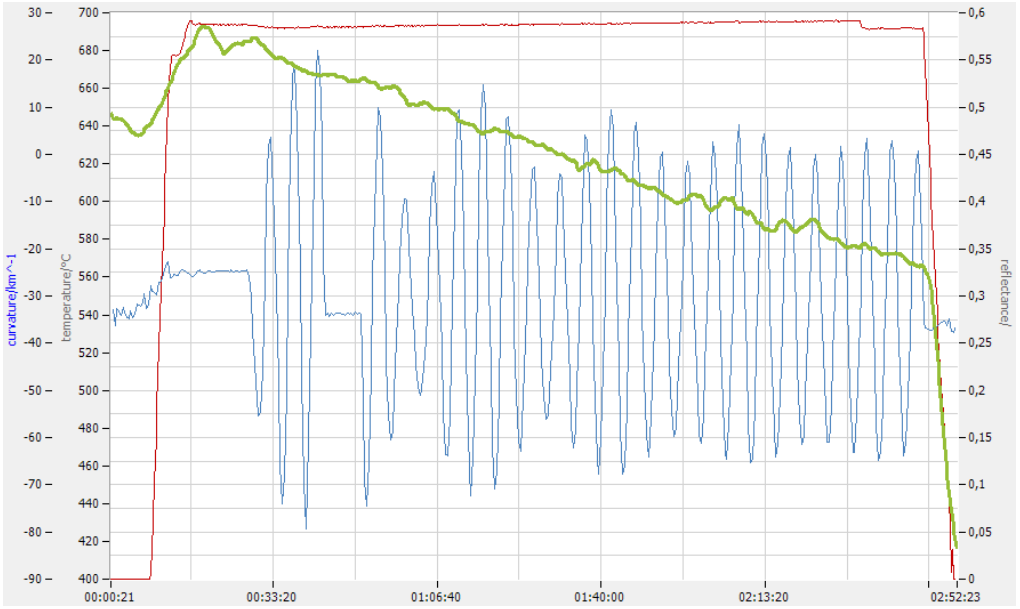
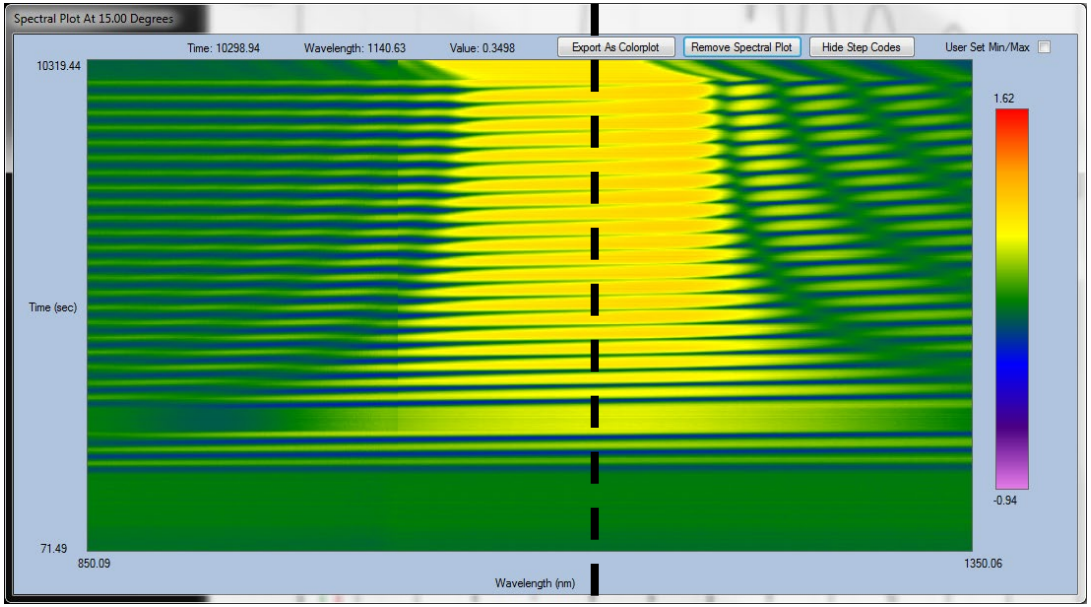
Exemplary DBR structure

- 25 GaAs / AlAs pairs
- Research reactor not fully optimized

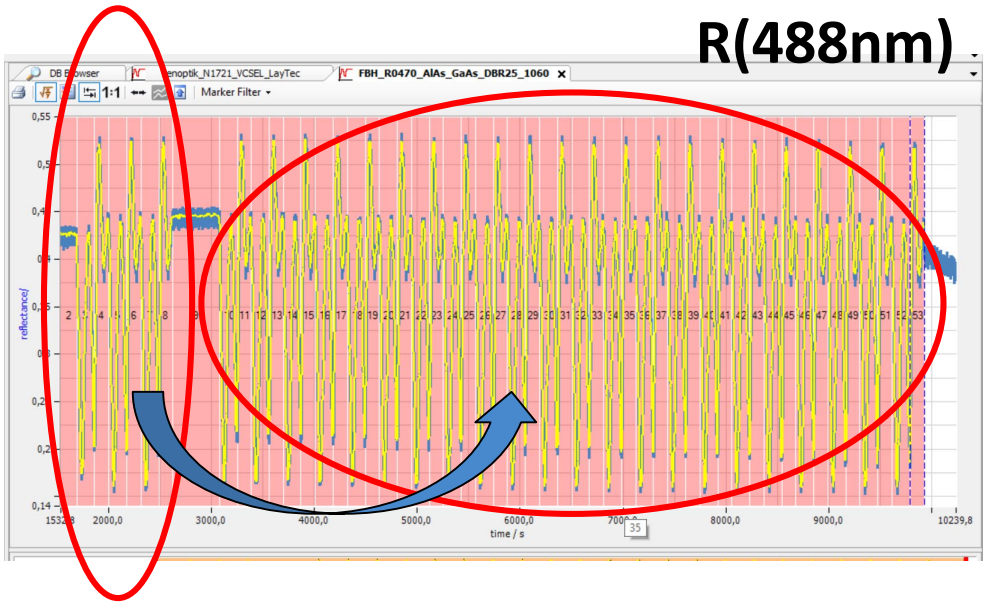




True Temperature
Reflectance 950nm
Curvature

LAYTEC Knowledge is key

SESAM DBR – feed-forward correction in Epi recipe

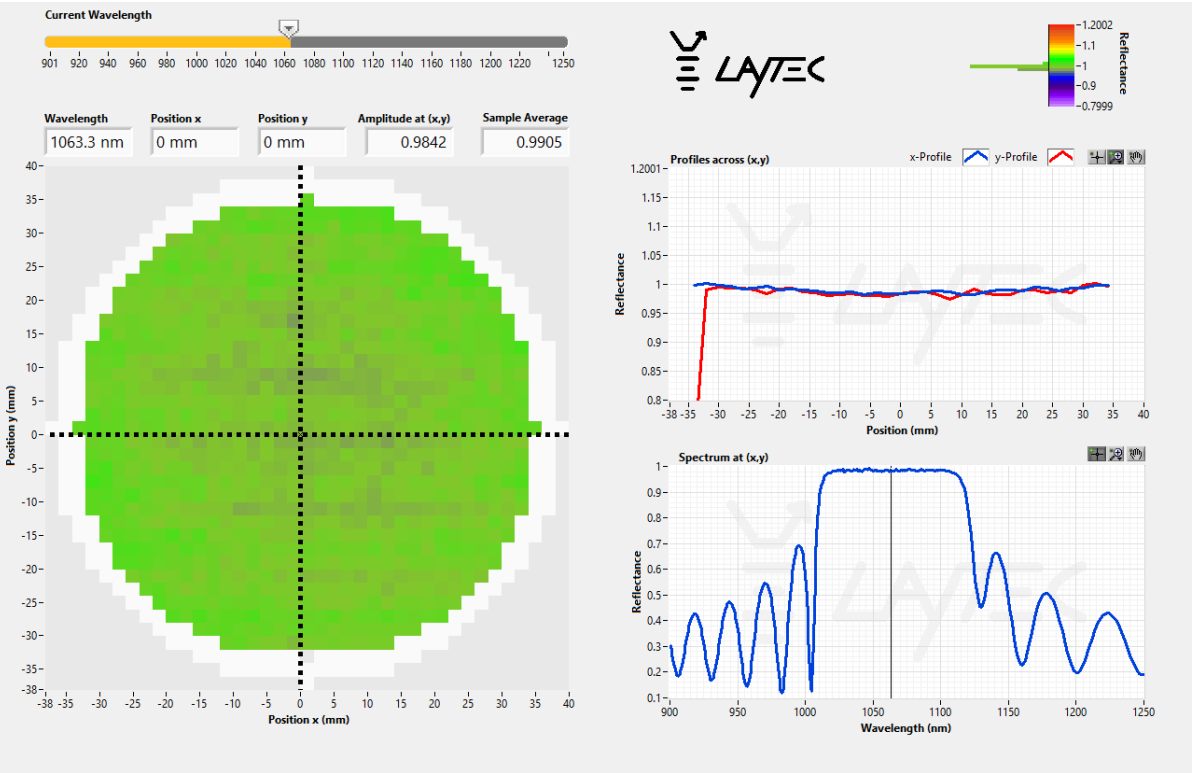


First 3 DBR periods: growthrates (GaAs, AlAs) in-situ measured: multi-λ, multi-layer, graded interfaces (if so)!

→ **latest version of AIXTRONs Aixact MOCVD software**

→ **feed forward recipe update (new settings) for remaining 22 periods**

Ex-situ analysis of the DBR structure



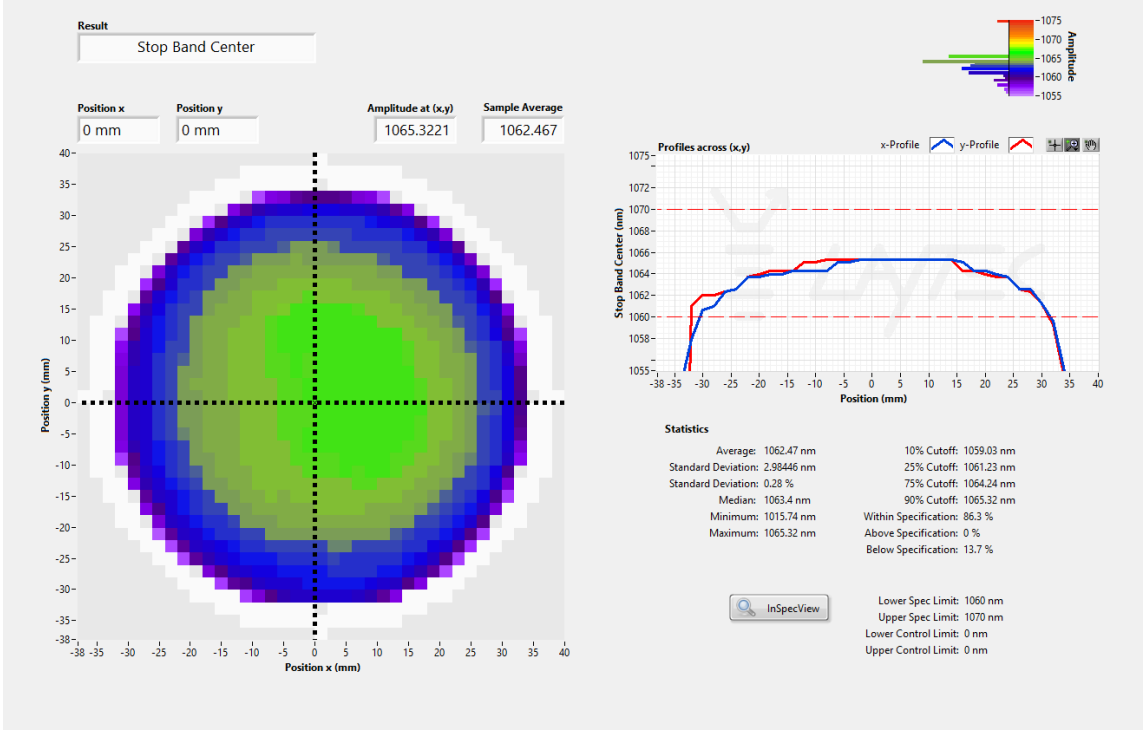
Reflectance map at 1050 nm

- 25 GaAs / AlAs pairs
- DBR centered around 1060 nm

Knowledge is key

LayTec VCSEL Fit – Stop Band parameters

- LayTec VCSEL Fit provides:
  - Stop Band center, edge wavelength and width
  - Maximum reflectance
  - If present: cavity dip center wavelength, width, amplitude and area



2D map of stop band center wavelength

Knowledge is key

LayTec VCSEL Fit – Stop Band parameters

- LayTec VCSEL Fit provides:
  - Stop Band center, edge wavelength and width
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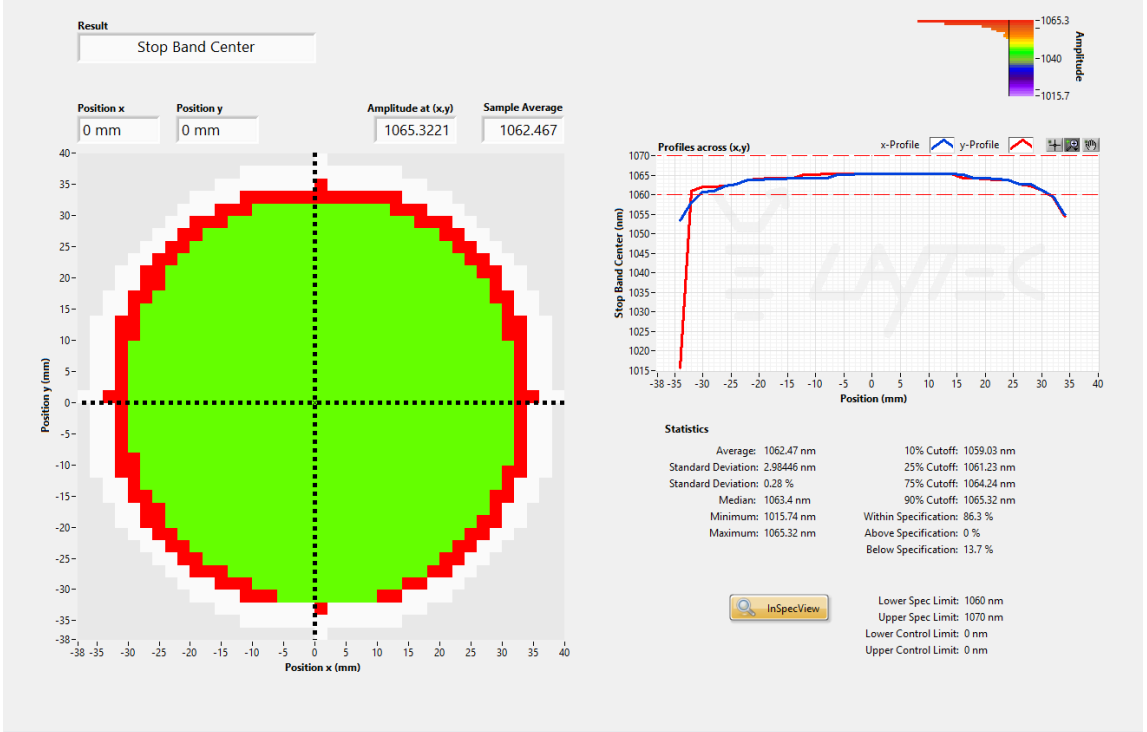
  - If present: cavity dip center wavelength, width, amplitude and area
  - Pass-fail classification on wafer-level and die-level

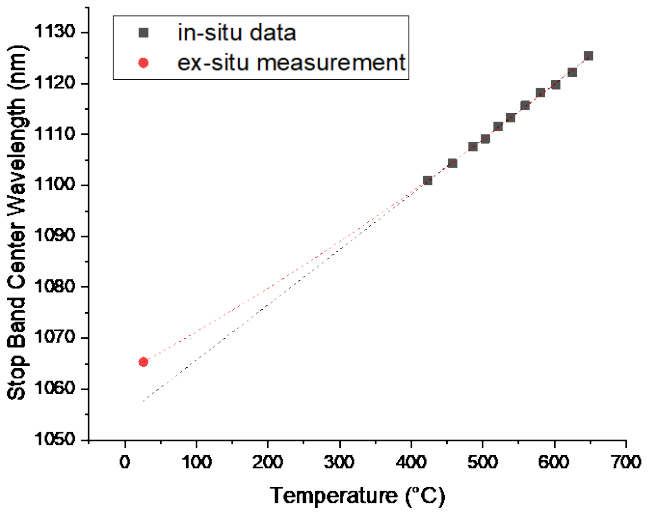


2D map of stop band center wavelength in pass-fail classification

LAYTEC Knowledge is key

LayTec VCSEL Fit – Stop Band parameters

- Determination of stop band center wavelength shift during cooldown
- Prediction of room temperature wavelength
- Linear extrapolation not sufficient as nk(T) is not linear
- Offset to linear approximation ≈ 8 nm



Extrapolation of Stop Band Center wavelength to room temperature

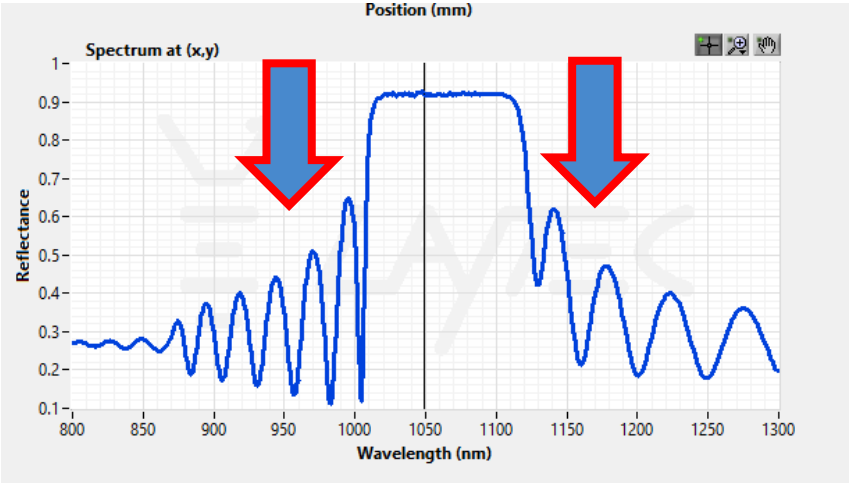
Understanding spectral peculiarities

Reflectance map at 1060 nm

- 25 GaAs / AlAs pairs
- DBR centered around 1060 nm

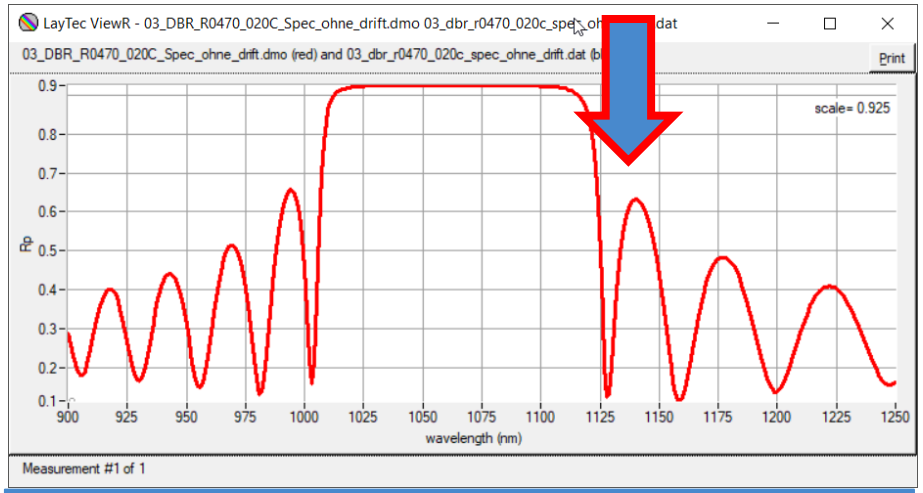
Knowledge is key

Understanding spectral peculiarities



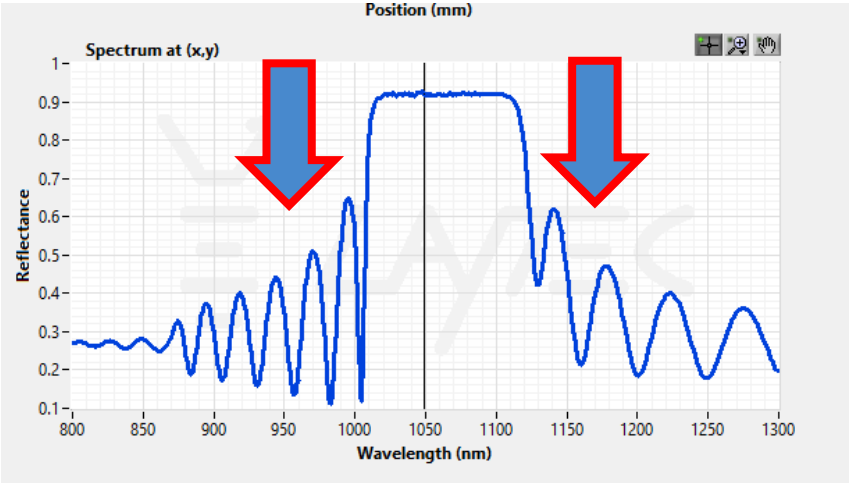
Reflectance map at 1050 nm

- DBR spectrum is asymmetric
- Analytic model of expected structure yields more symmetric spectrum



Model of DBR as intended

Understanding spectral peculiarities



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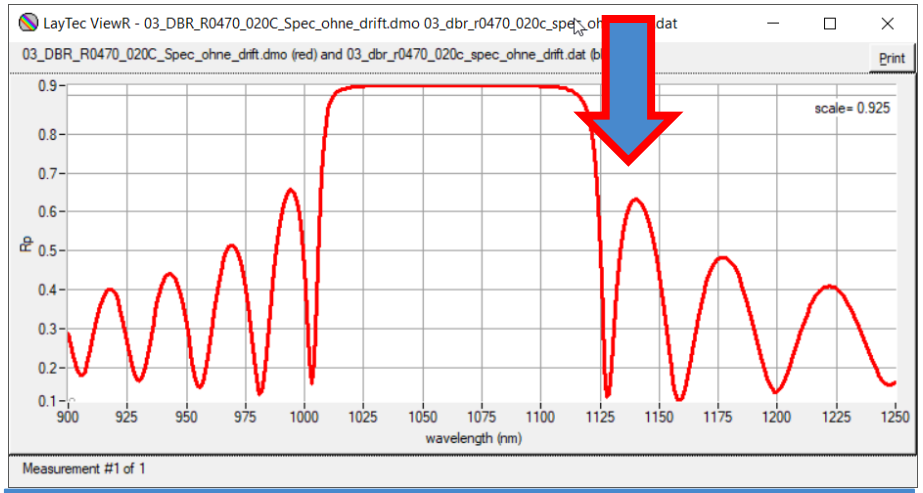
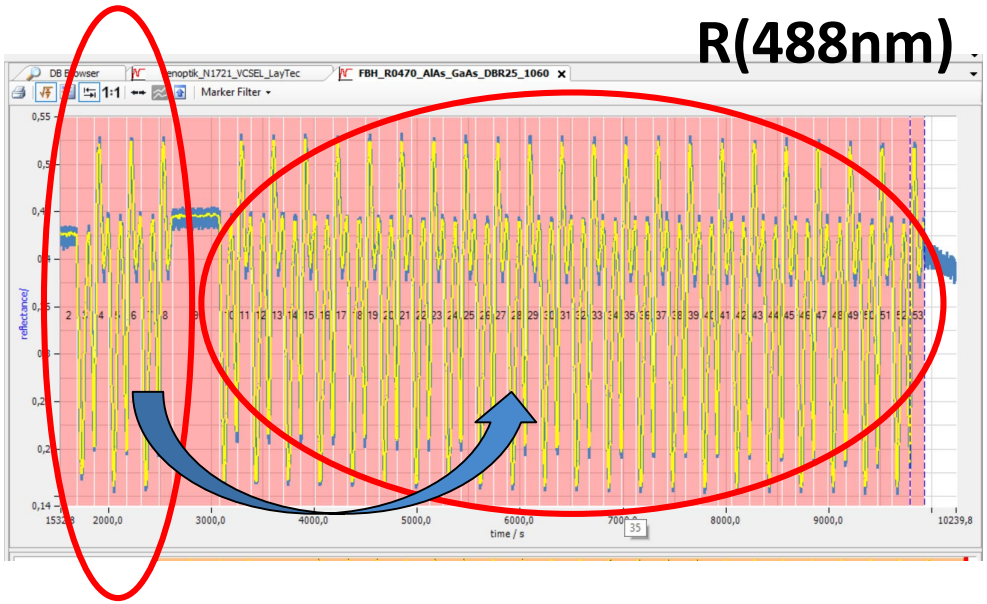


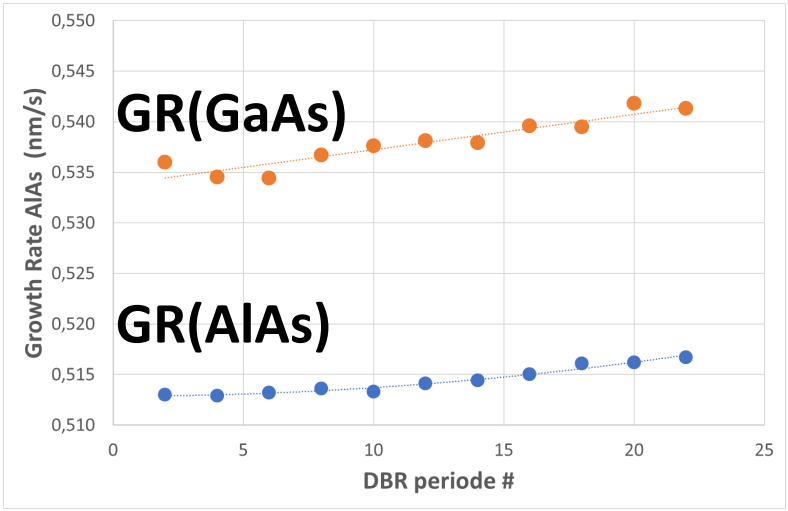
Model of DBR as intended

Let us look at the in-situ data again…

LAYTEC Knowledge is key

SESAM DBR – feed-forward correction in Epi recipe





First 3 DBR periods: growthrates (GaAs, AlAs) in-situ measured: multi-λ, multi-layer, graded interfaces (if so)!

→ **latest version of AIXTRONs Aixact MOCVD software**

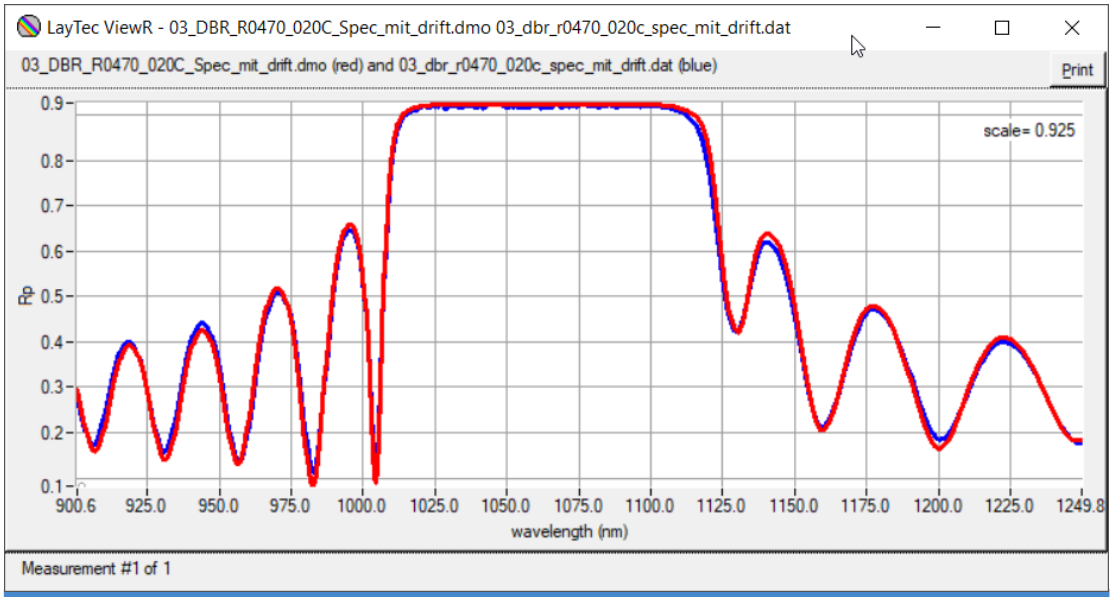
→ **feed foreward recipe update (new settings) for remaining 22 periods**

To be taken into account for feed-foreward recipe update: the tiny but reproducible change in GRs (measured in-situ by advanved algorithms) during DBR growth

Leibniz Ferdinand Braun Institut FBH

LAYTEC Knowledge is key

Understanding spectral peculiarities



Model of DBR taking into account minor growth rate drifts

Analytic model of DBR structure taking into account the growth rate drifts yields excellent agreement to **measured spectrum.**

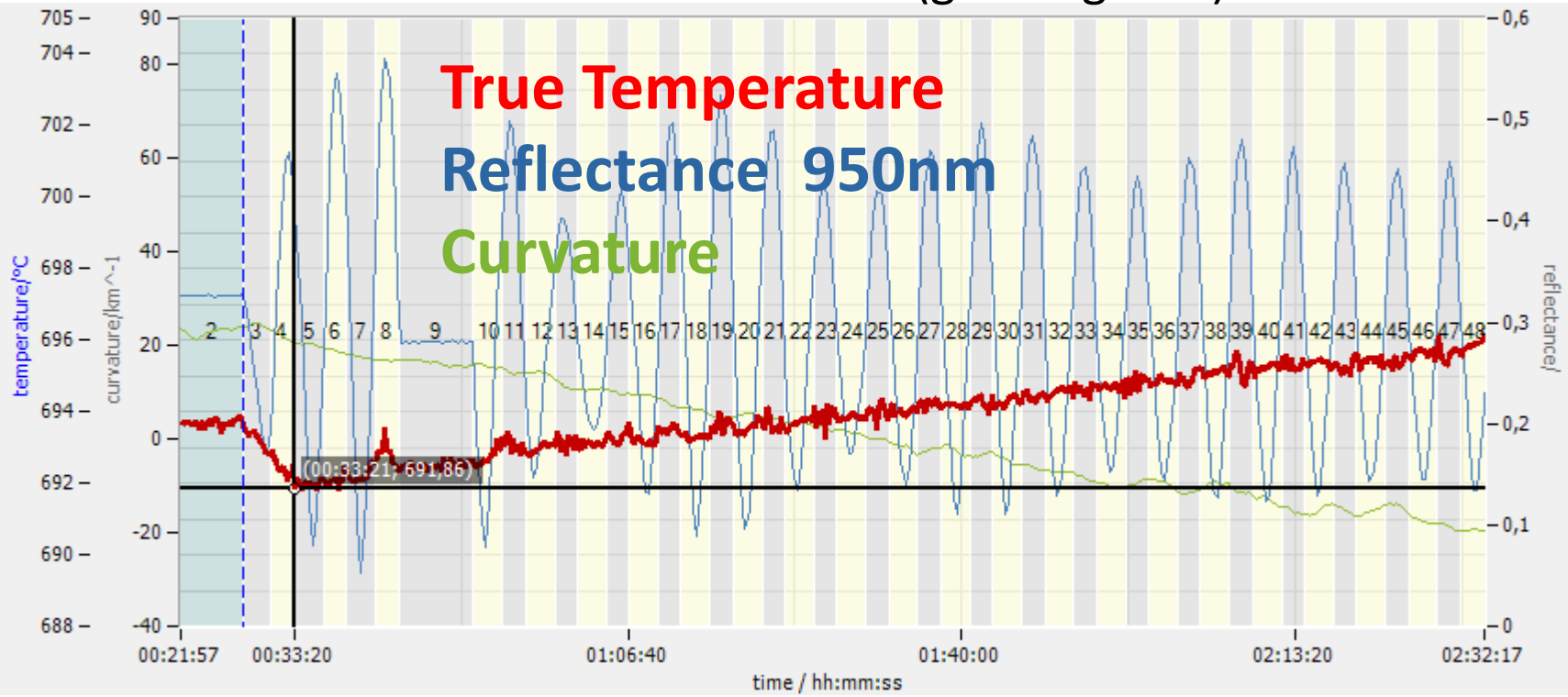
Growth rate AlAs: 0,4955 nm/s at start → 0,4990 nm/s at end (1%)

Growth rate GaAs: 0,5769 nm/s at start → 0,5839 nm/s at end (1%)

LAYTEC Knowledge is key

Why growth rate is changing during DBR?

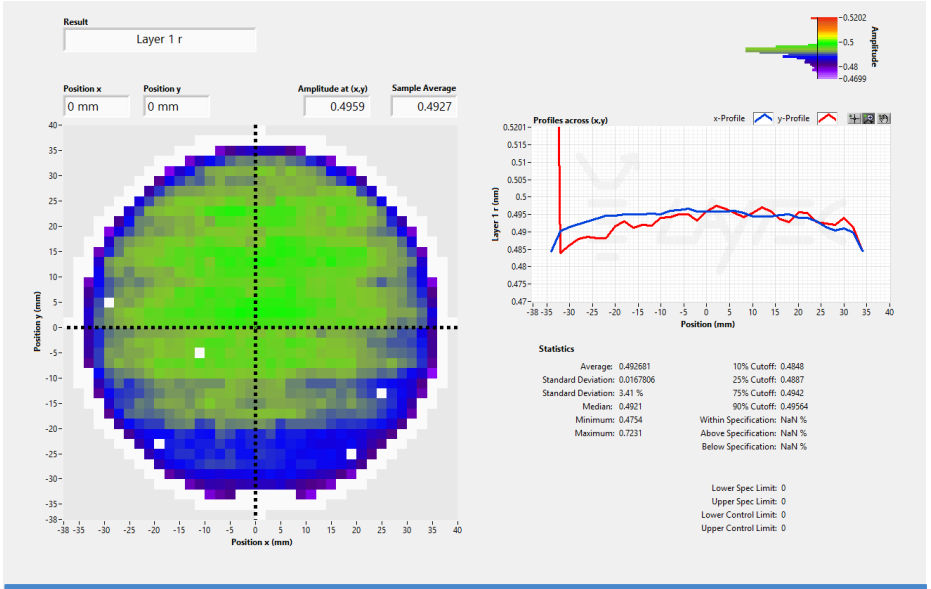
- Wafer is bowing during DBR growth (compressive strain in AlAs/GaAs stack)
- Thermal emission of wafer is reduced (growing DBR)



Knowledge is key

DBR Growth rate analysis – 2d + time

- Feeding back analytic model into EPIX software facilitates the 2D analysis of the key DBR growth rates



2D map of AlAs growth rate: 1% deviation center to edge

Growth rate AlAs Center:

- 0,4955 nm/s at start
- 0,4990 nm/s at end

Growth rate AlAs Edge:

- 0,4840 nm/s at start
- 0,4874 nm/s at end

→2% center to edge

→1% start to end

Synergizing ex-situ and in-situ analyses facilitate the correlation of inhomogeneities to actual growth parameters

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DBR Growth rate analysis – 2d + time

- Feeding back analytic model into EPIX software facilitates the 2D analysis of the key DBR growth rates

2D map of AlAs growth rate: 1% deviation center to edge

<u>Growth rate GaAs Center:</u>

- 0,5769 nm/s at start
- 0,5839 nm/s at end

<u>Growth rate GaAs Flat:</u>

- 0,5850 nm/s at start
- 0,5920 nm/s at end

→1% center to edge

→1% start to end

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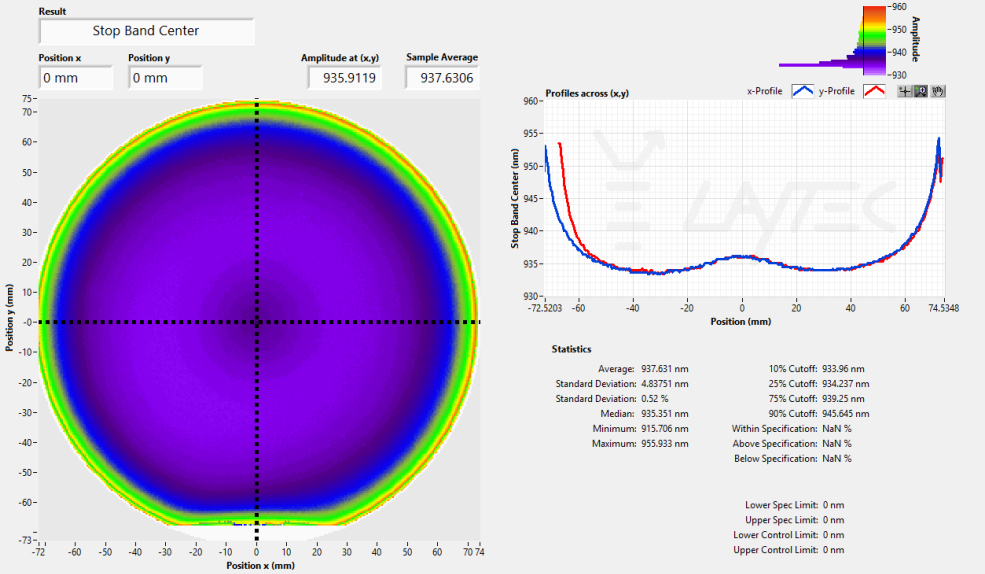
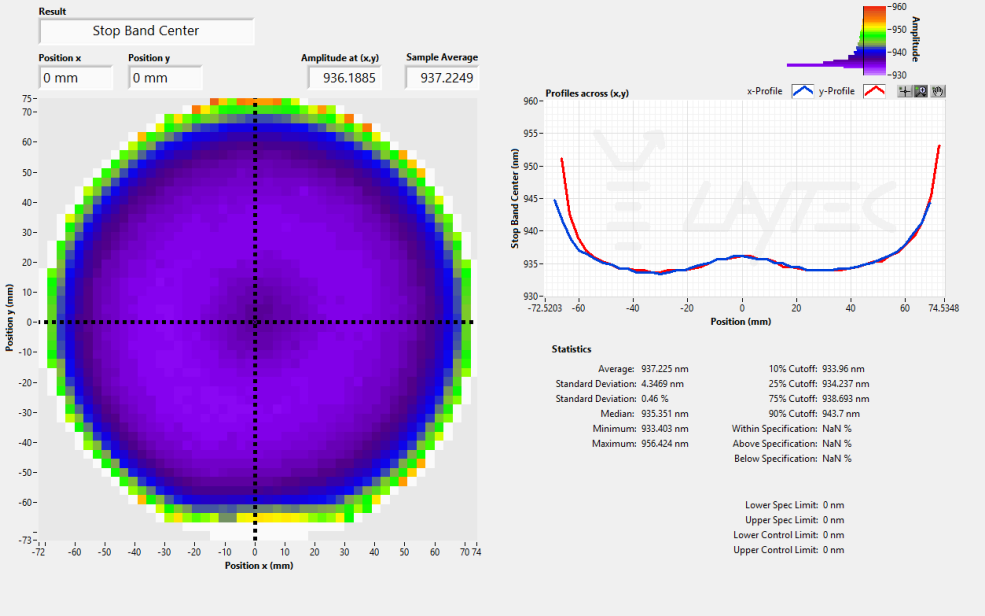
Interpolation of measurement results



2D map of stop band center wavelength measured at 0.5 mm pitch

- 2D measurement of wafers at **low pitches requires measurement time**
- **Key parameters** usually **change gradually**

Interpolation of measurement results

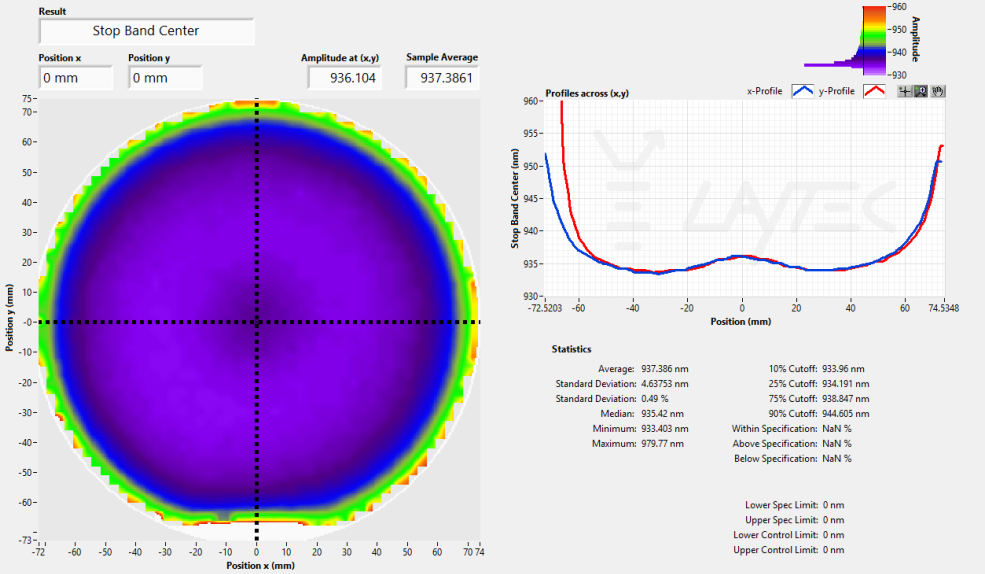


2D map of stop band center wavelength measured at 3 mm pitch

- 2D measurement of wafers at **low pitches requires measurement time**
- **Key parameters** usually **change gradually**
- Lowering pitch from 0.5 mm to 3 mm **reduces number of points by factor of 36**

LAYTEC Knowledge is key

Interpolation of measurement results

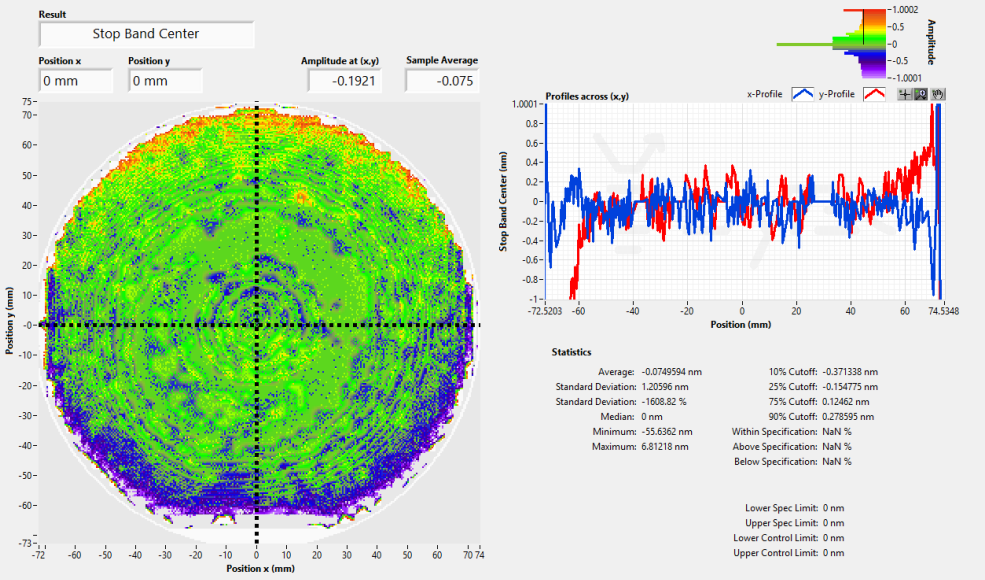


2D map of stop band center wavelength measured at 3 mm pitch, interpolated to 0.5 mm

- 2D measurement of wafers at **low pitches requires measurement time**
- **Key parameters** usually **change gradually**
- Lowering pitch from 0.5 mm to 3 mm **reduces number of points by factor of 36**
- Interpolation of analysis results facilitates **accurate yield analysis even for low dies sizes**

LAYTEC Knowledge is key

Interpolation of measurement results



Deviation caused by interpolation smaller than 0.25 nm, i.e. , smaller than the spectral resolution

- 2D measurement of wafers at **low pitches requires measurement time**
- **Key parameters** usually **change gradually**
- Lowering pitch from 0.5 mm to 3 mm **reduces number of points by factor of 36**
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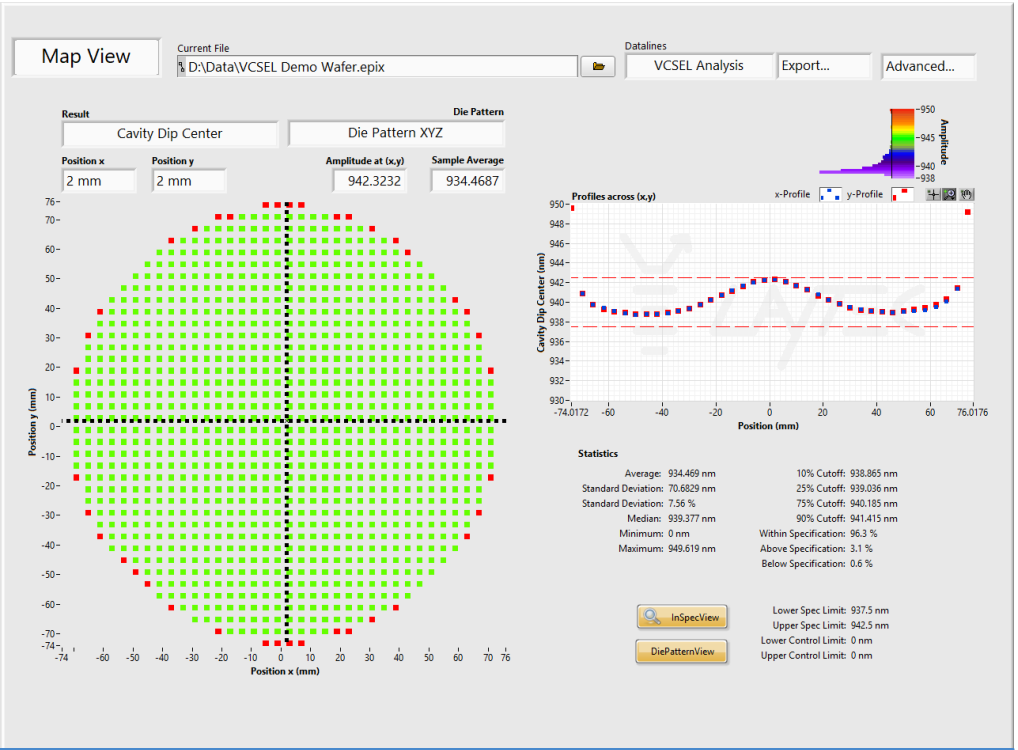
Interpolation of measurement results



Pass-fail classification at die level

- Interpolation of analysis results facilitates accurate yield analysis even for low dies sizes

Interpolation of 3 mm pitch measurement reduces measurement time by a factor of ~36 at the cost of < ±0.25 nm accuracy

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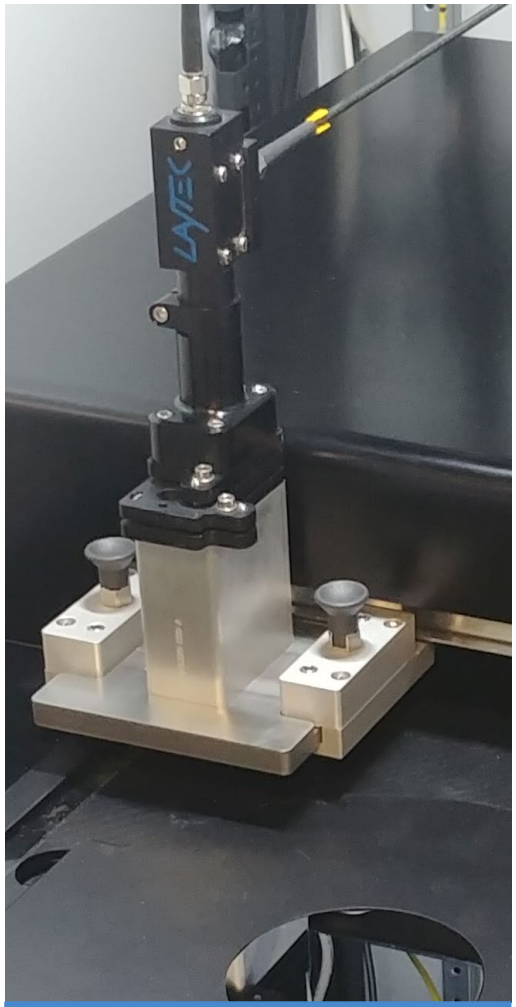
LayTec EPIX – for 2D mapping of III-V epi wafers

LayTec EPIX system

Measurements	white light reflectance (WLR) photoluminescence (PL)
Sample size	up to 8“
Spectral range	400-1700 nm (Si+InGaAs array)
Scan speed	up to 17 spectra/s
Other features	vacuum chuck for wafer holding auto-configuration of integration times interlock and emergency stop touch-based interface
Software	recipe-based measurements / analyses inSpec view / die pattern view XML reports /ASCII exports
Footprint:	2000 x 1000 x 1100 mm

LAYTEC Knowledge is key

LayTec EPIX – White light reflectance measurements

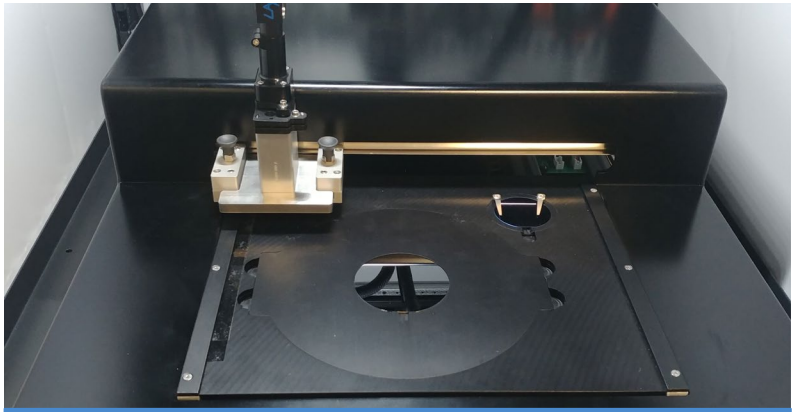


Fiber optical reflectance head mounted on EPIX

Excitation: Tungsten light source

Normalization: Auto-normalization using reference sample

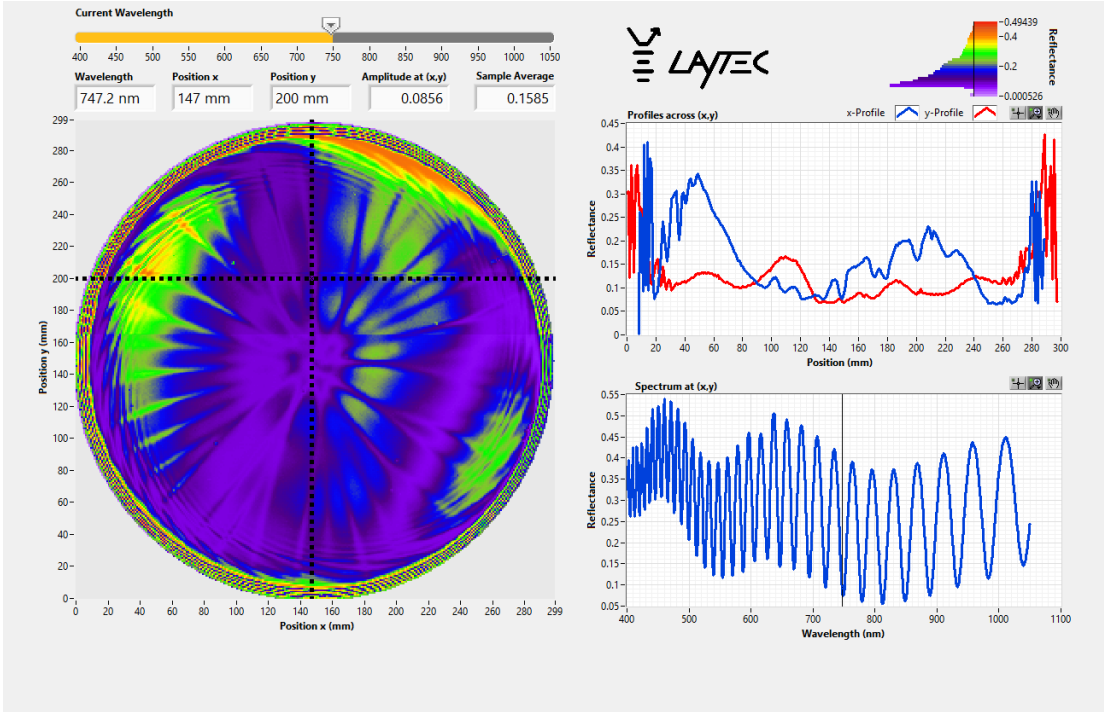
Options: Measurements on both wafer sides and transmittance measurements possible



Mapping stage with 3“ sample holder plate

LAYTEC Knowledge is key

RAW Data View



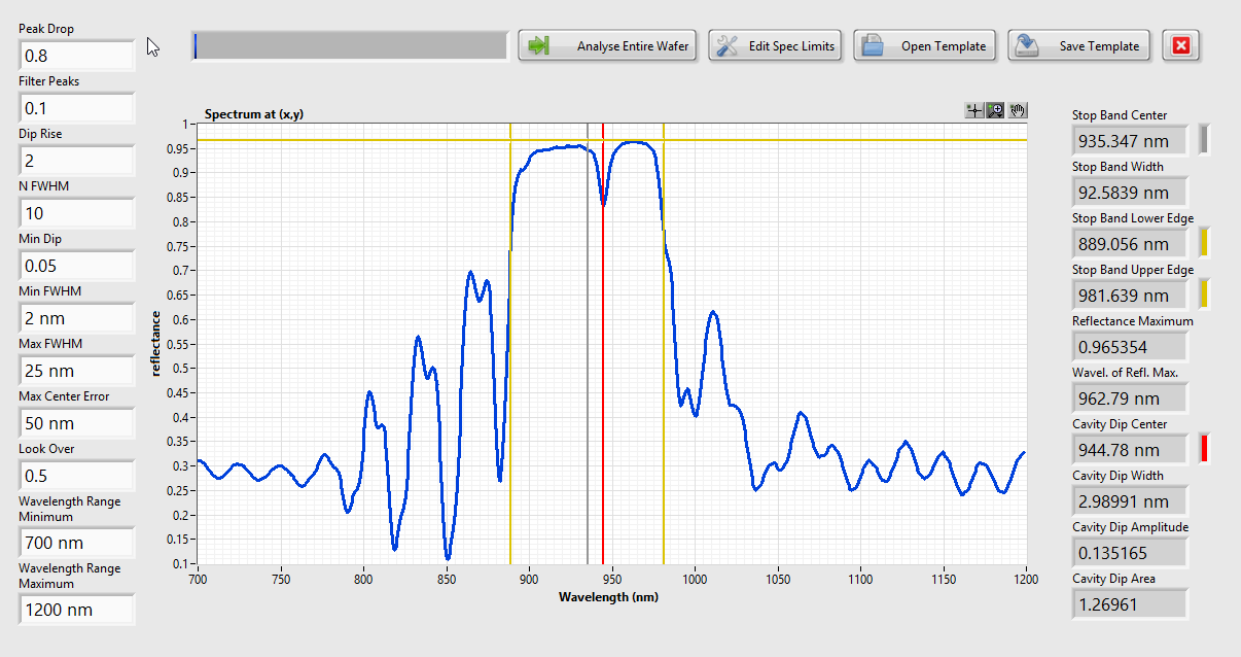
Raw reflectance data view of sample with spincoated photo resist film

raw data view for all wavelength

- X/Y profiles and spectra
- edge exclusion
- ASCII export

Knowledge is key

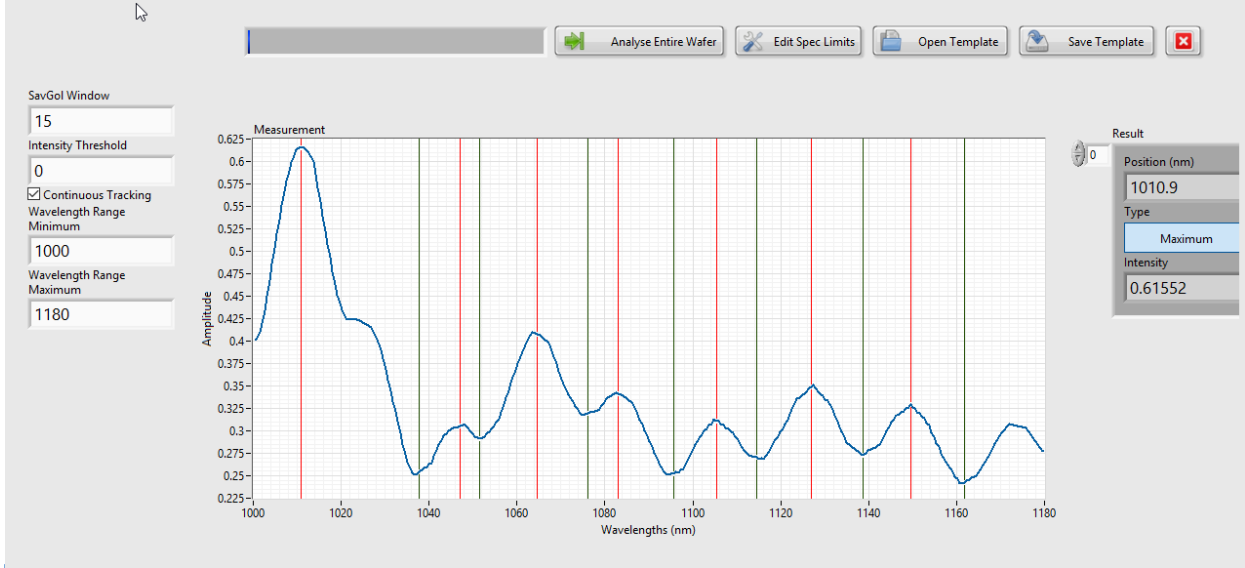
VCSEL Analysis



Spectral analysis for VCSELs

- Identical to in-situ analysis in EpiNet for EpiTT VCSEL
- Determines stop band center, edges and height, cavity dip center, width, amplitude and area

Extrema Tracking

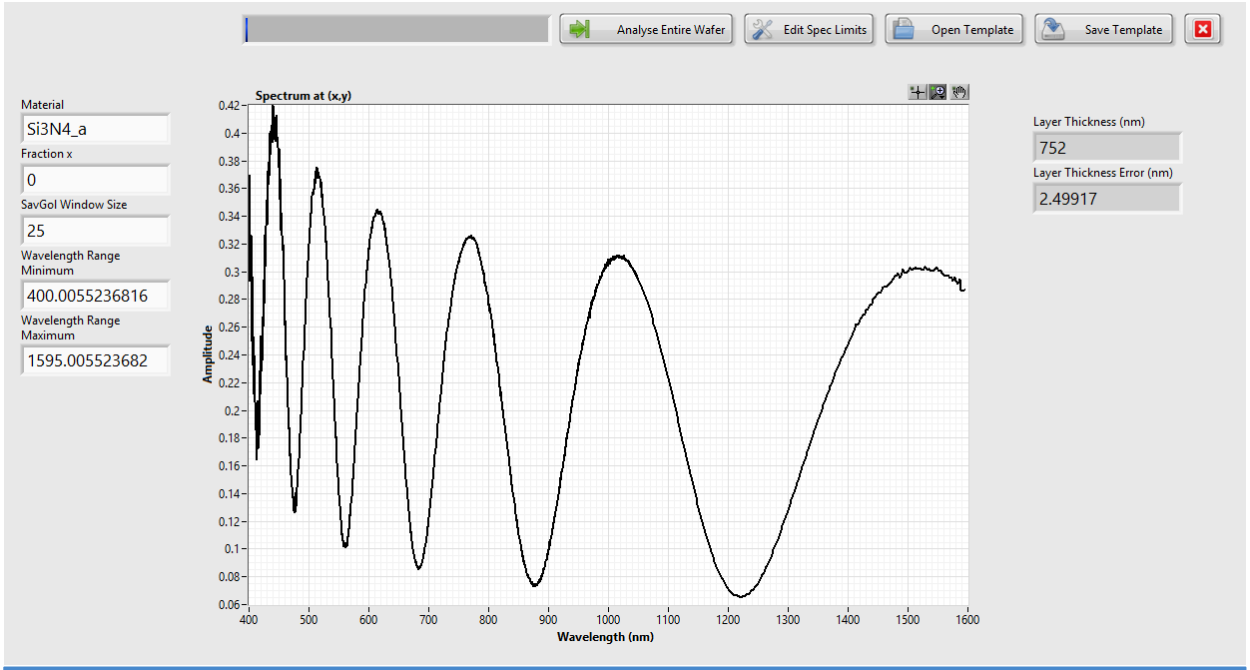


General spectral analysis – monitor extrema positions

- Monitoring of extrema positions
- Track drift of extrema positions and intensity across wafer
- useful for VCSEL side lobes

Knowledge is key

Single Layer Thickness Fit

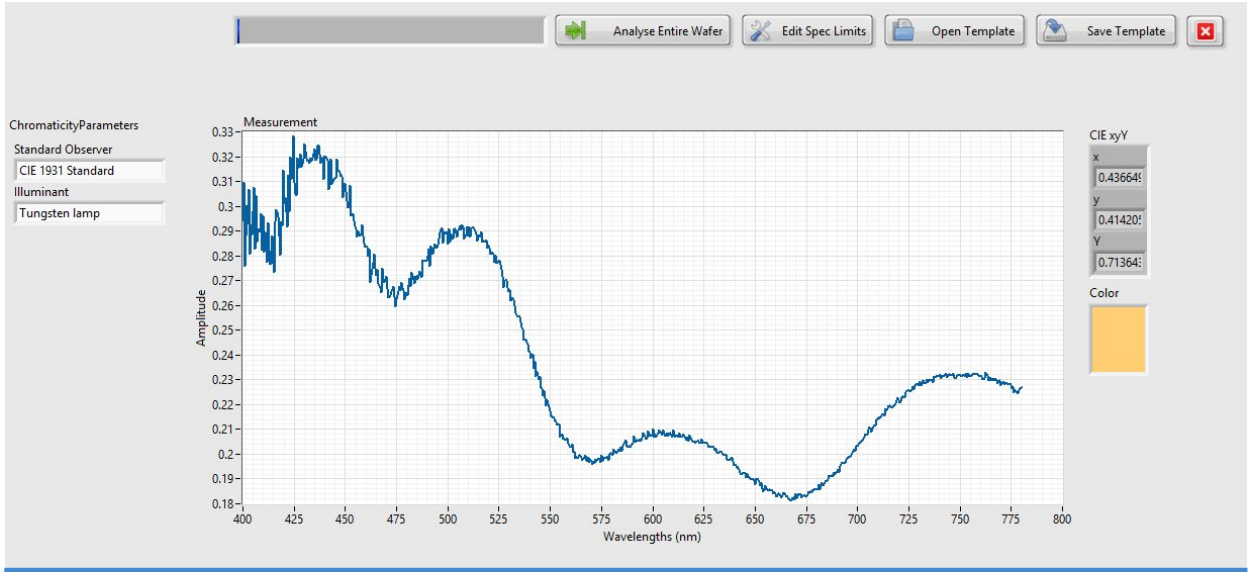


Single layer thickness fit

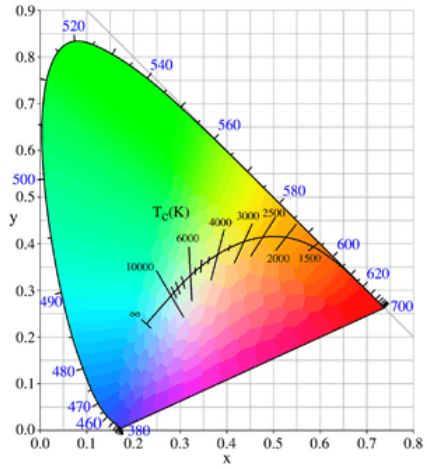
- Fast thickness determination of single layer film thicknesses using LayTec's nk database
- Advanced options for 2-Layer and Multi-Layer Thickness and Composition Fits available

Knowledge is key

Chromaticity calculation



Single layer thickness fit



- Measure the color coordinates of any sample
- Usable on reflectance and luminescence measurements

Knowledge is key

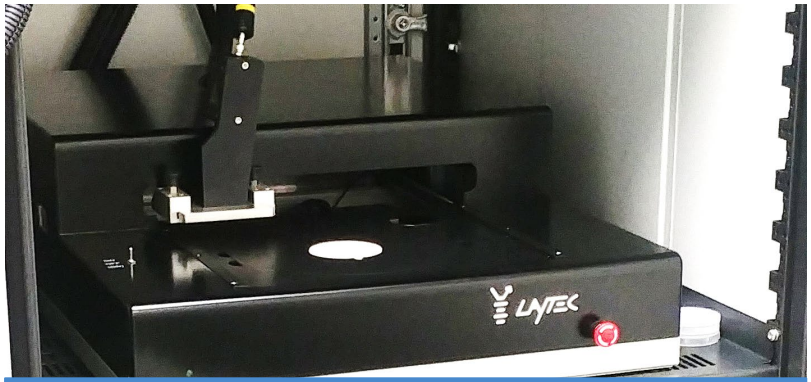
LayTec EPIX – Photoluminescence measurements

Mapping stage, WLR and PL controller

PL excitation: up to 4 laser sources configurable
405 / 532 / 638 / 808 nm available
other wavelength upon request
specific PL measurment heads

Attenuation: 6 excitation levels (OD0-OD4)

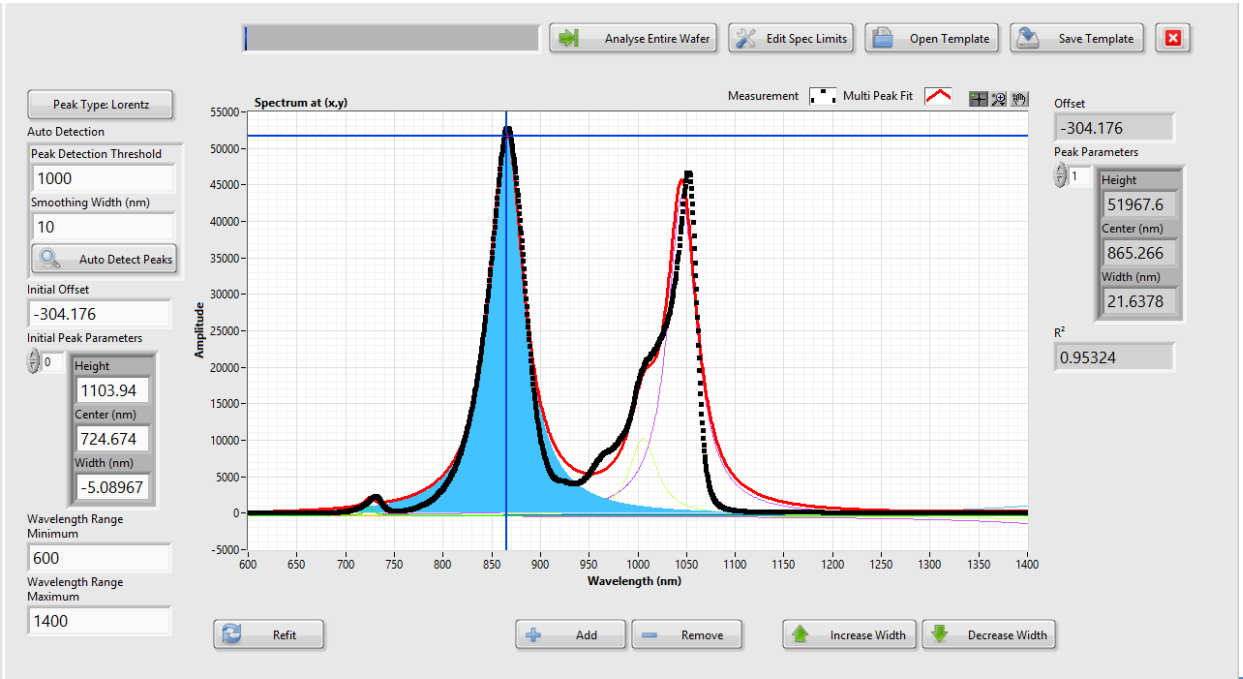
Laser Class 1: lasers radiation (<500mW) is blocked within EpiX and secured by interlocks and emergency stop



PL measurement head mounted on mapping stage

Knowledge is key

Multi-Peak Fit



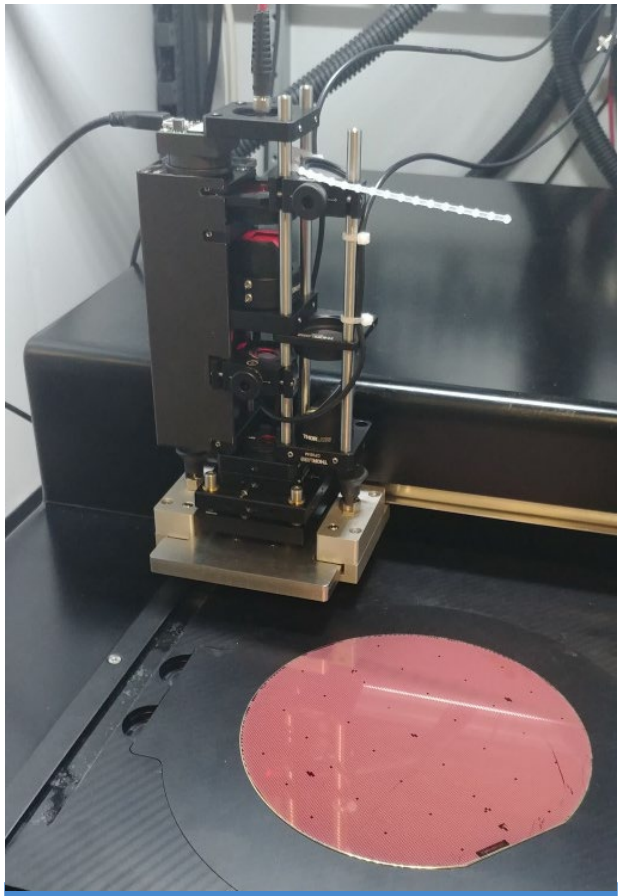
Multi-Peak Fit

- Analysis of luminescence spectra
- Superposition of multiple peaks
- Peaks may be fitted as Lorentzians or Gaussians or analyzed numerically

Knowledge is key

Upgrade modules – additional measurements

- Wafer bow
- Reflectance-Anisotropy
- Sheet resistance
- Wafer thickness
- Optical transmission

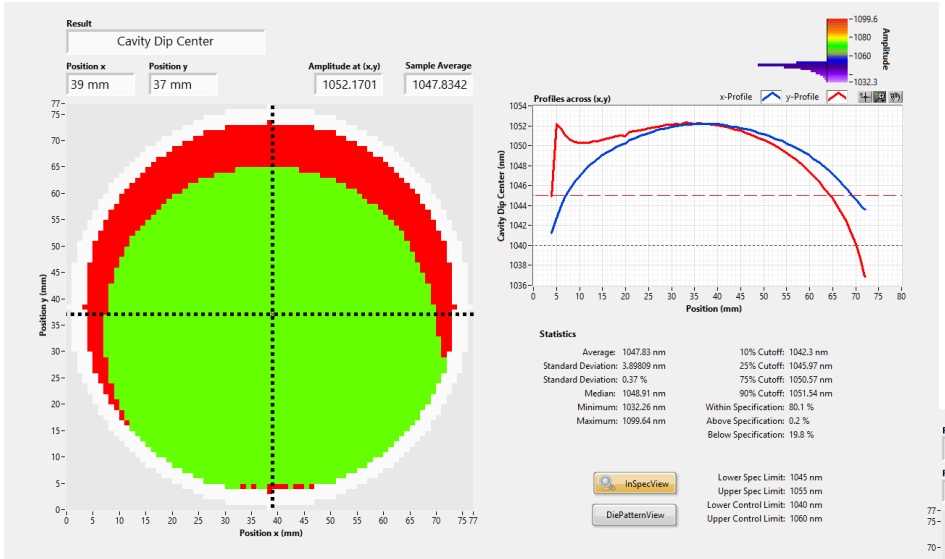


2D RAS measurement module integrated in EPIX mapping station

Software modules

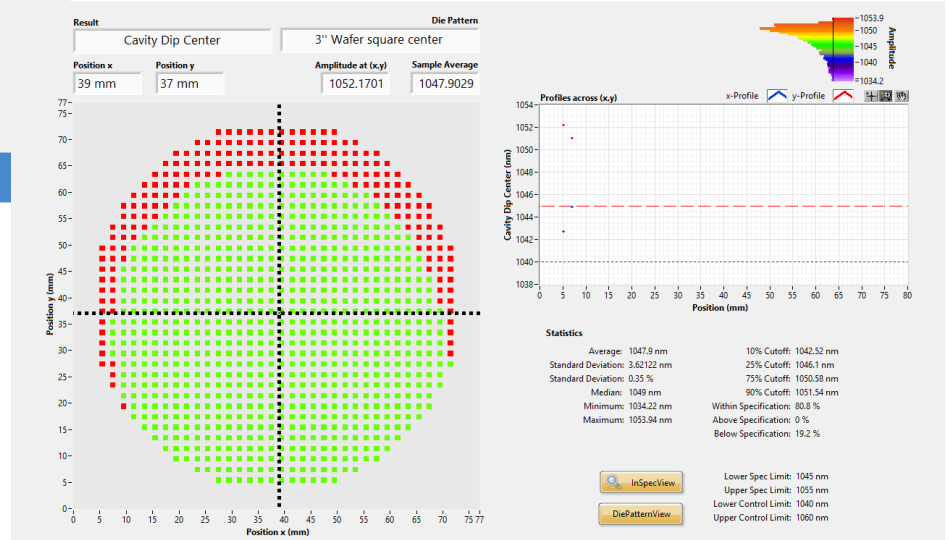
- Many spectral analysis
- Application of virtual die patterns for die-level analysis
- LabView API to integrate user-owned spectral analysis libraries
- EpiNet interface for using in-situ data measured during epitaxy in center of wafer as starting point for post-epi 2D mapping analysis

Automated yield analysis using LayTec EPIX



InSpecView: color coding analysis results to specifications

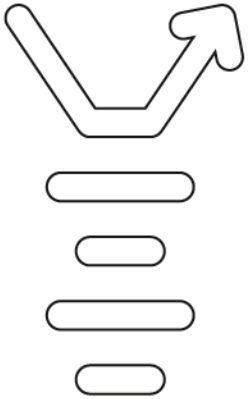
- 2D pass/fail classification
- Die pattern assignment
- XML reports



DiePatternView: Applying virtual die patterns to wafer maps

Knowledge is key

Knowledge is key



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