In-situ metrology for advanced process control and equipment health monitoring in semiconductor epitaxy

Dr. Kolja Haberland

Chief Technology Officer
LayTec AG

Knowledge is key

Outline

Introduction
– Two semiconductor industries
– Types of metrology

In-situ metrology and control in Compound Semiconductor Epitaxy
– Integration of metrology
– In-situ metrology techniques
– From data to information
– Application examples

Opportunities for in-situ metrology and control in Si Semiconductor Industry

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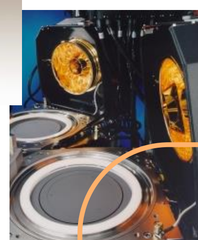
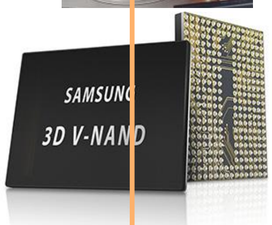
The Semiconductor Industries

Si Industry / Semi
„the big brother“

200mm/300mm
450mm (?)

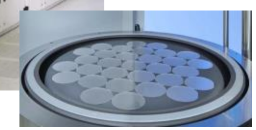




PECVD, ALD ....

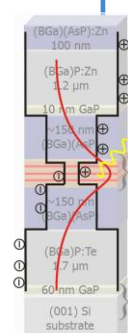
Compound Semiconductor
„the little brother“

2“/3“
100mm/150m



MOCVD, MBE

III/V on Si
„something from both“



MOCVD

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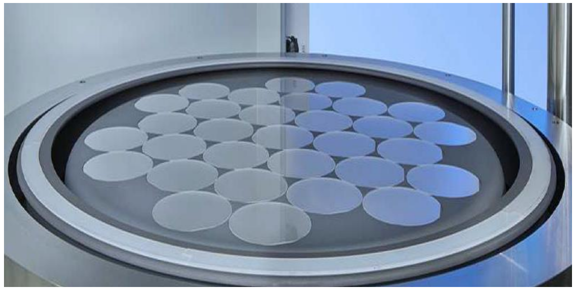
Equipment and automation

FOUPs
and automated wafer loading

4x300mm

robot transfer of manually loaded carriers



31x4“

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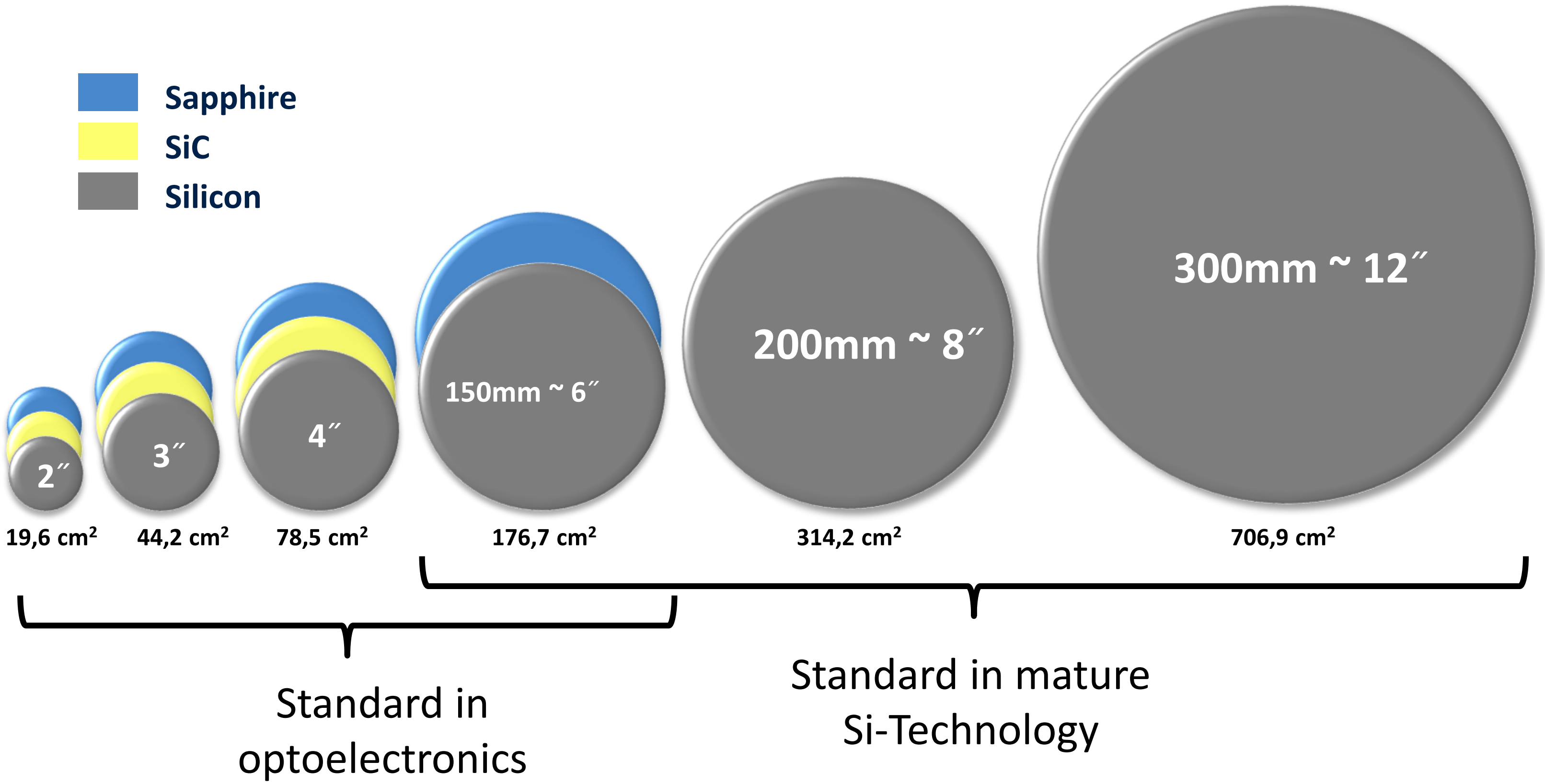
Wafer sizes



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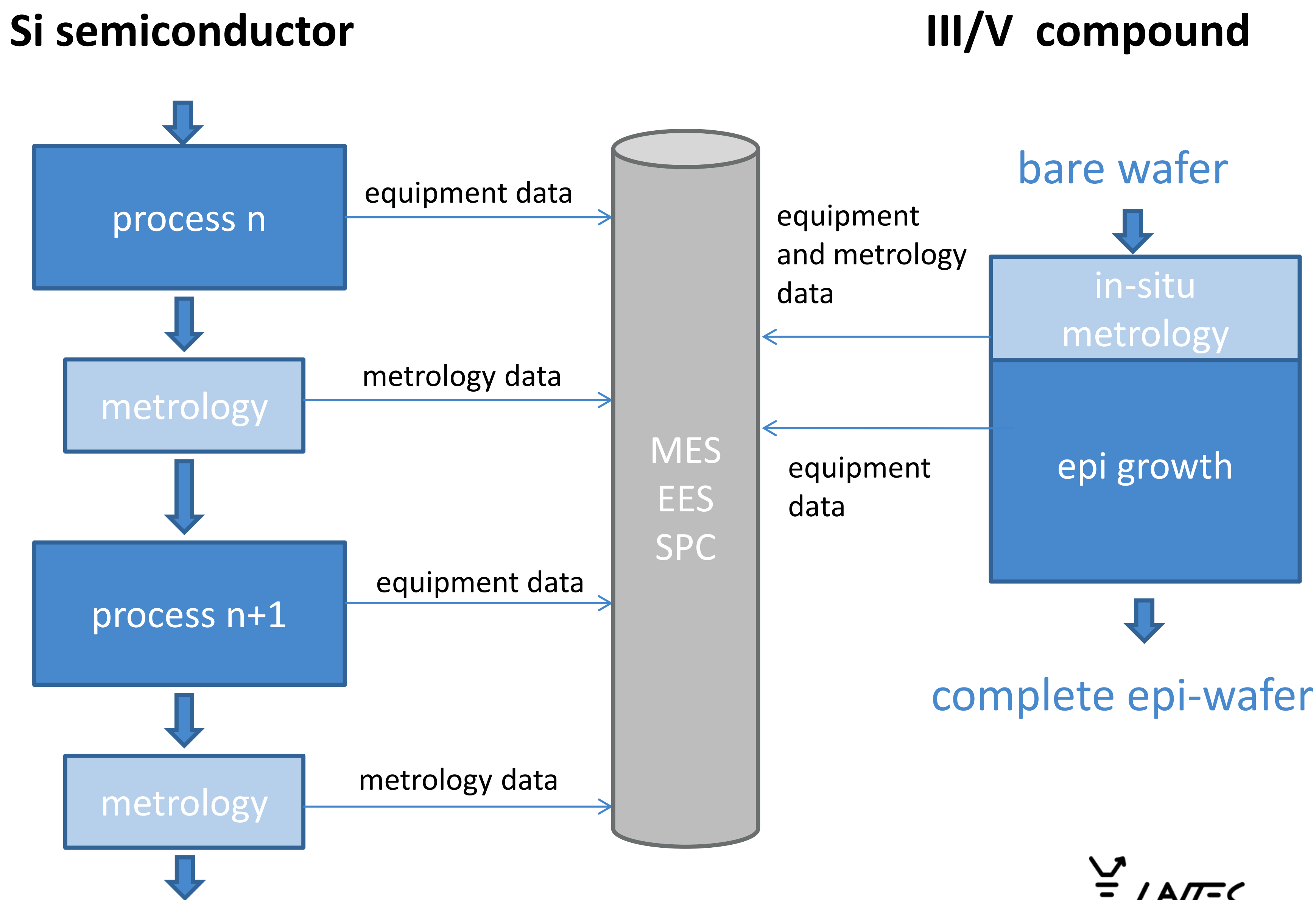

Knowledge is key

Compound semiconductor vs. Semi market

	Compound (CS)	Traditional Semi
Wafer size	(2"), 3", 4", 6"	150/200/300mm, (450mm)
Growth run duration	~6-8 hours	~1 min
Number of layers per run	~20...>100	1
Number of wafers per run	10...50	1
Level of automation	Low, increasing	Fully
Level of fab integration	Low, increasing	High
Yield managing strategies	Evolving	Excellent

Still very different markets – but they are getting closer!

- In CS strong demand for in-situ monitoring, control and automation
- Established APC concepts from Semi market are entering CS market
- In Semi, multi-layer Epi for next generation devices
- New applications for in-situ monitoring
- Common goals: higher yield, lower cost

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Metrology …

Semi

Virtual metrology

… methods to predict properties of a wafer based on machine parameters and sensor data of the production equipment, without performing the (costly) physical measurement on the wafer

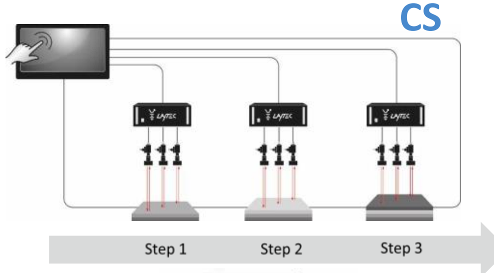
Integrated metrology

… still needs a universal definition, it has become the term associated with the slow migration from offline to inline and in situ measurements (ITRS 2013) ... anything "inside a tool"

CS

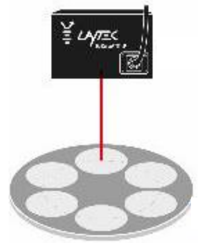
In-line metrology

… performed between process steps, i.e. before/after growth or deposition, to characterize wafer/layer properties,
e.g. in transfer chamber



In-situ metrology

… performed during process steps, i.e. during growth or deposition, to characterize wafer/layer and process properties,
i.e. in growth chamber



ITRS 2013 – metrology section

- The fundamental challenge for factory metrology will be the **measurement and control of atomic dimensions** while maintaining profitable **high volume manufacturing**
- Although **integrated metrology still needs a universal definition**, it has become the term associated with the **slow migration from offline to inline and in situ** measurements.
- The proper combination of **offline, inline, and in situ measurements** will enable advanced process control and rapid yield learning.
- The **relationship between metrology and process technology development needs fundamental restructuring**.
- Understanding the **interaction between metrology data and information and optimum feed back, feed forward, and real time process control are key** to restructuring the relationship between metrology and process technology.

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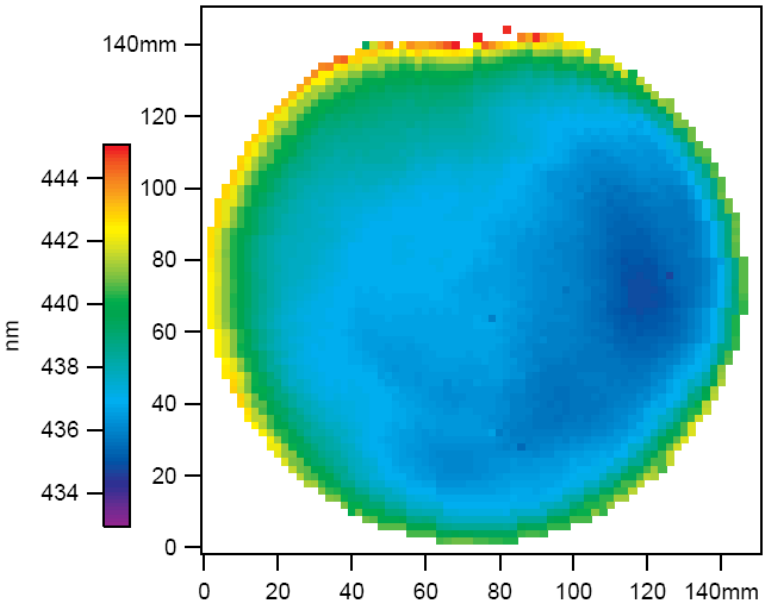
Process control: What is it all about?



ex-situ photoluminescence map of 6" LED wafer after epi (example)

It's all about:

- cost reduction
- improving yield (e.g. LED emission wavelength being on target)
- on-wafer uniformity
- wafer-2-wafer uniformity
- run-2-run control
- tool matching
- reduced downtime (e.g. for maintenance/calibration runs)

You need to monitor and control:

- pocket temperature and wafer temperature
- wafer curvature / wafer bow
- layer thickness and uniformity, ternary composition ...

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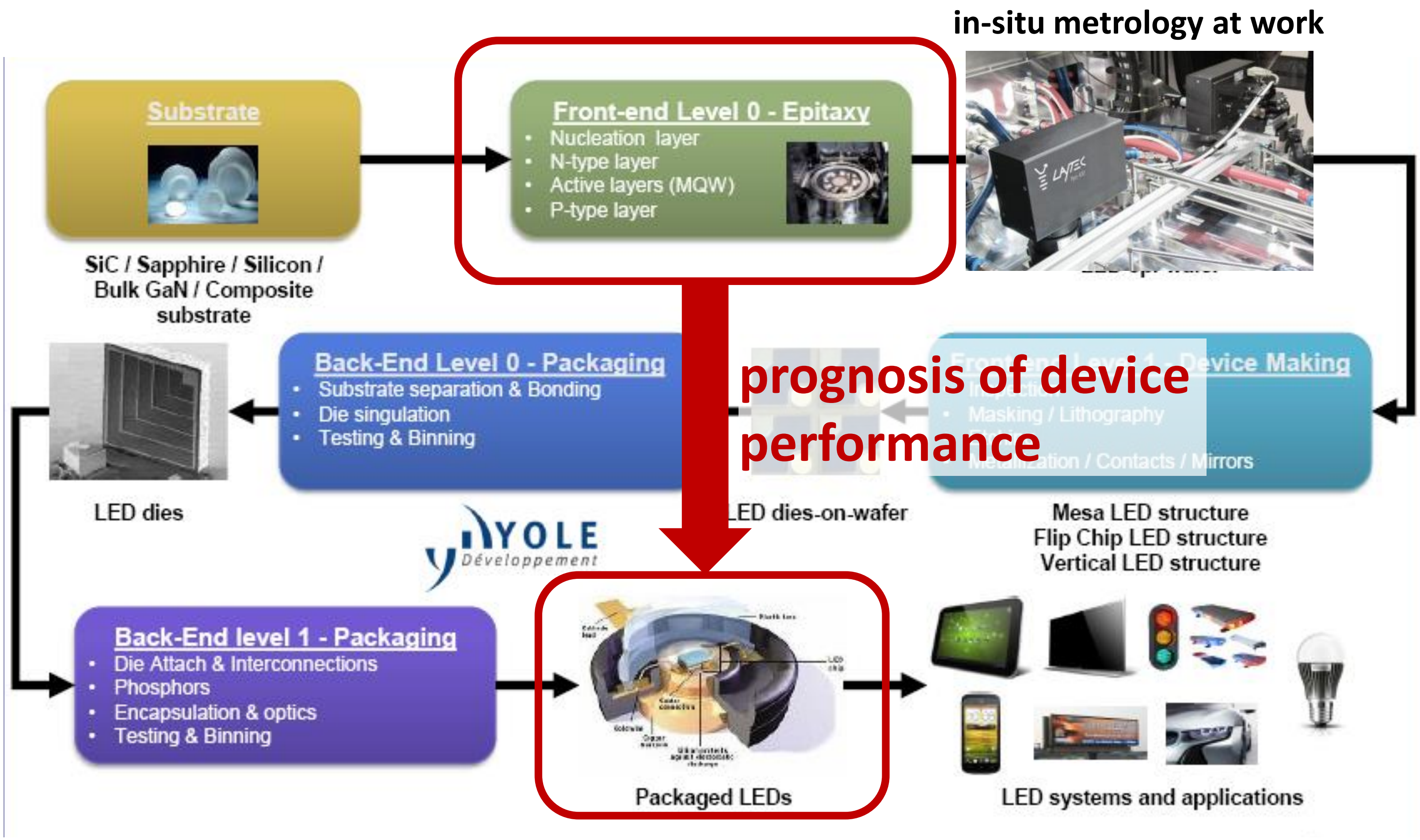
LED Manufacturing Process Overview



acc. to Yole 2014: "LED Front-End Manufacturing Trends"

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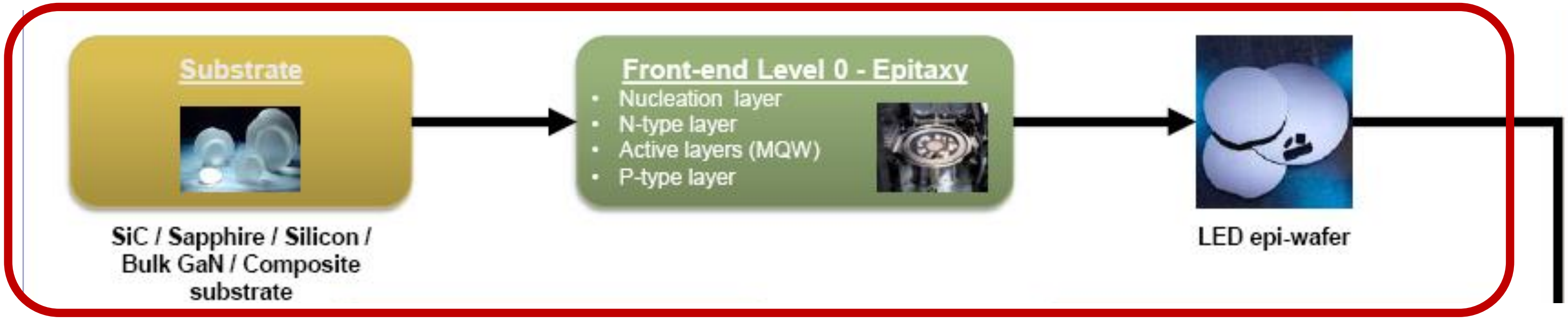
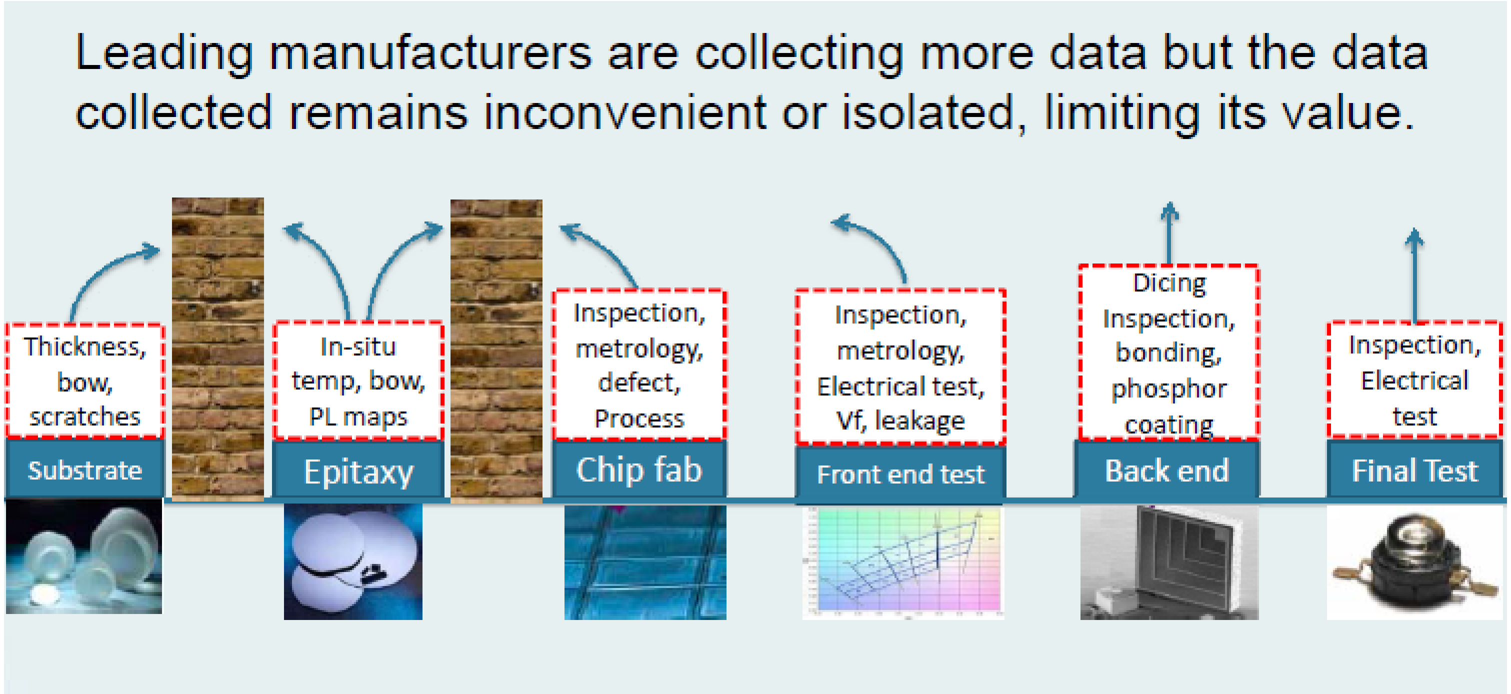
LED Manufacturing Process Overview



What is different to Semi industry?

- High complexity and added value in epitaxy
- All layers are deposited in one single growth run (~ hours)
- Simultaneous growth on multiple wafers
- Layer structures usually too complex to be characterized ex-situ
- In-situ metrology has developped to be an essential part of process control
- Closed loop and feed back procedures based on in-situ data available within tool
- No strong differentiation between „equipment/tool data“ and „metrology data“ in process control
- However: in back end (chip processing) things are different ...

Status of APC in LED manufacturing

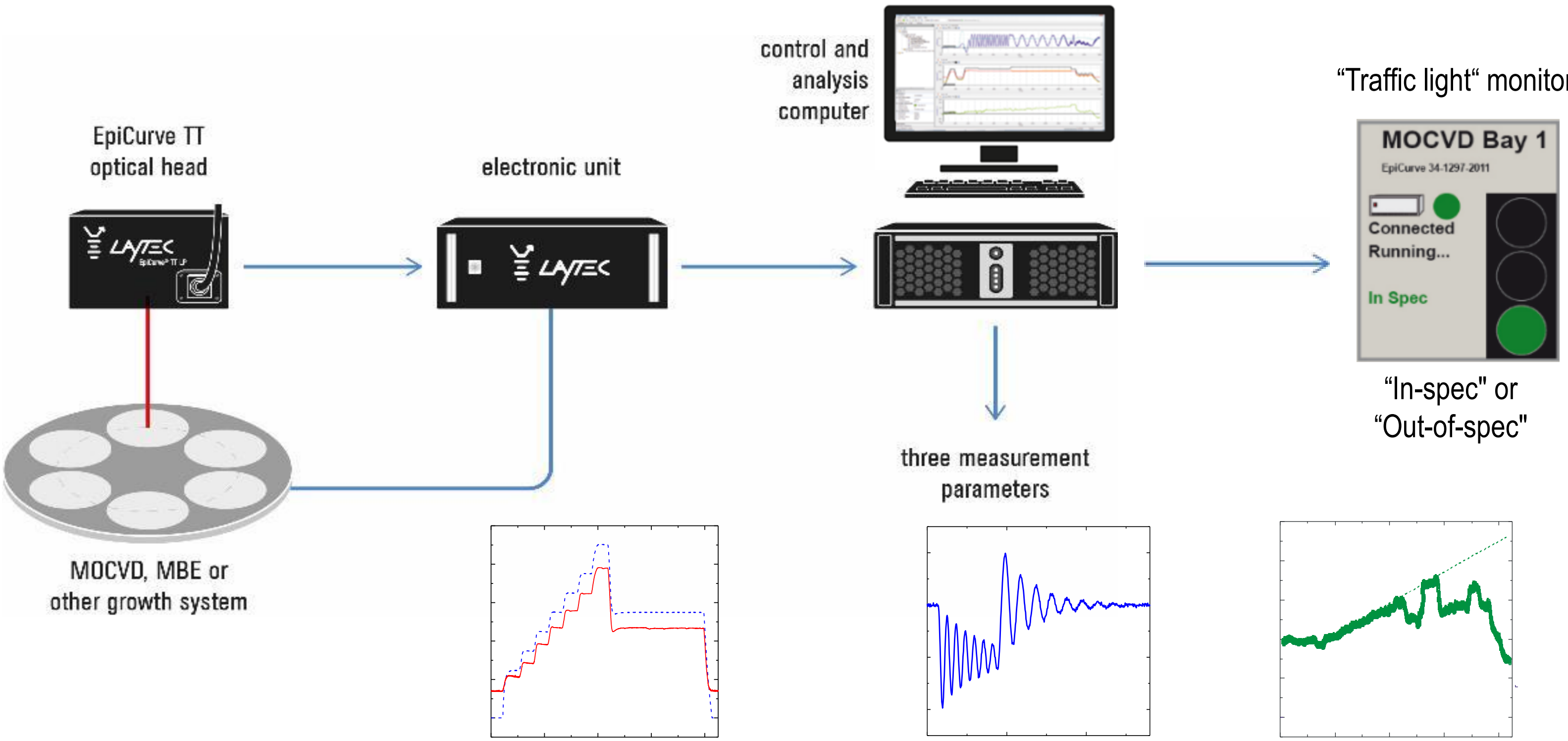


Source: Mike Plisinski, Rudolph Tech., Strategies in Light 2012

2012: In-situ data were not used downstream ...

2016: Things are changing ... fab-wide APC is starting ...

In-situ products for compound semiconductor market



IR and UV pyrometry (emissivity corrected)

3λ reflectance (405, 633, 950nm)

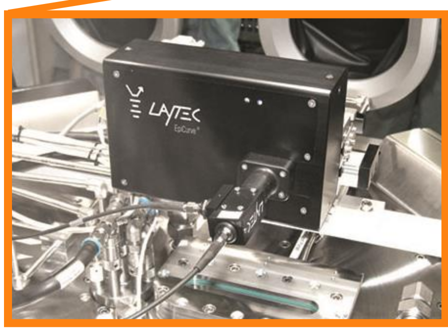
Wafer bow

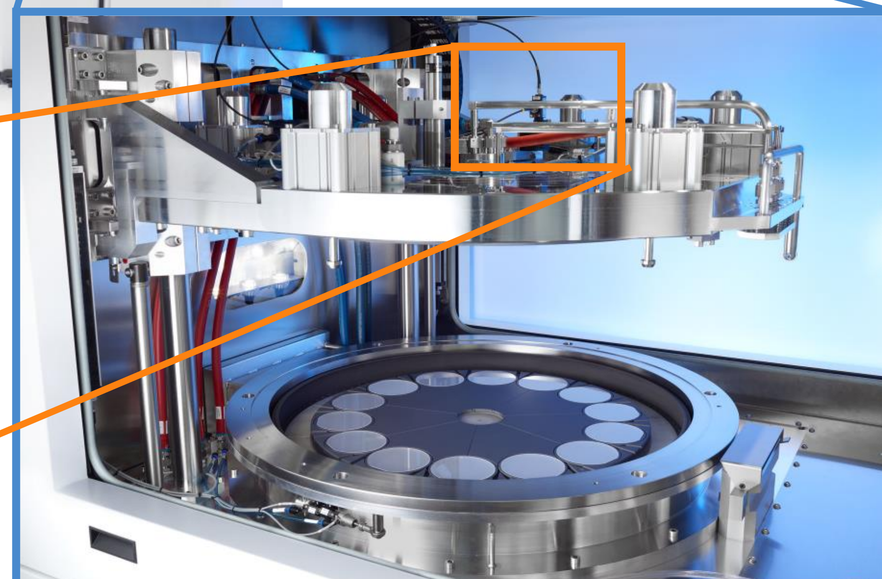
Knowledge is key

In-situ metrology fully integrated

MOCVD growth system (example)

In-situ tool





LayTec: 15 years of experience (installed base ~2000 systems)

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State-of-the-art: Top side temperature control in MOCVD

- AIXTRON R6 MOCVD system is equipped with four metrology heads *Inside TTC* to measure top side susceptor temperature (plus up to three *Inside MiniRC* for reflectance and curvature)
- additional viewport for *Inside P400* (UV pyrometer) to measure the GaN surface temperature (“wafer temperature”)
- PLC based close loop control in MOCVD system

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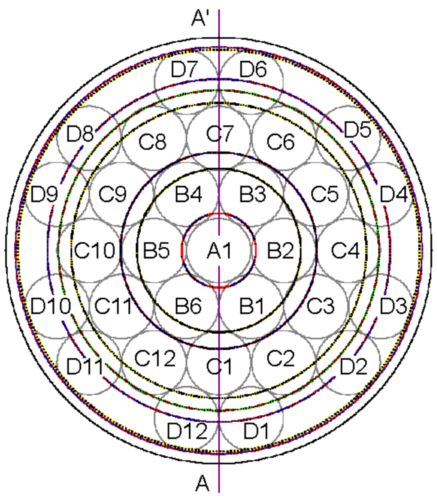
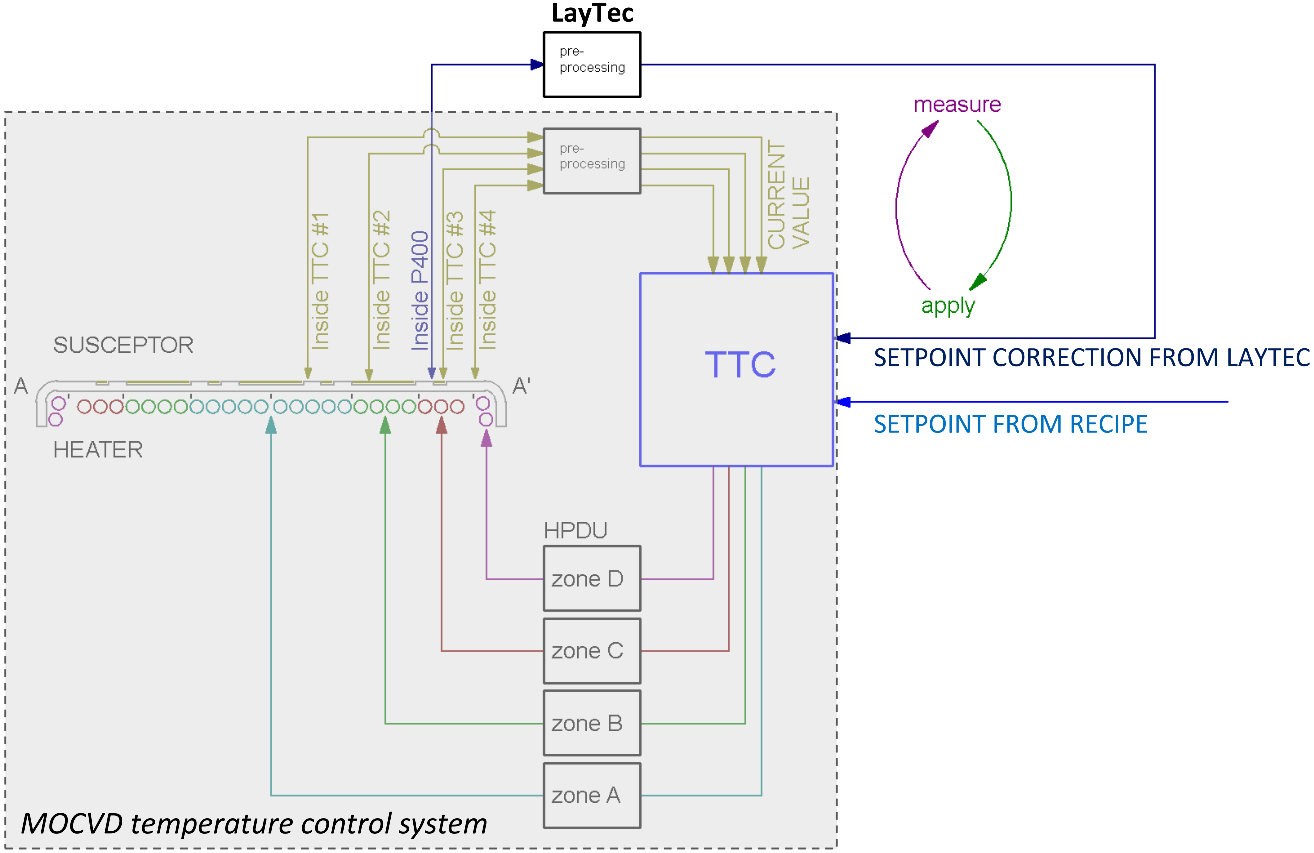
State of the art top side temperature control in AIX R6

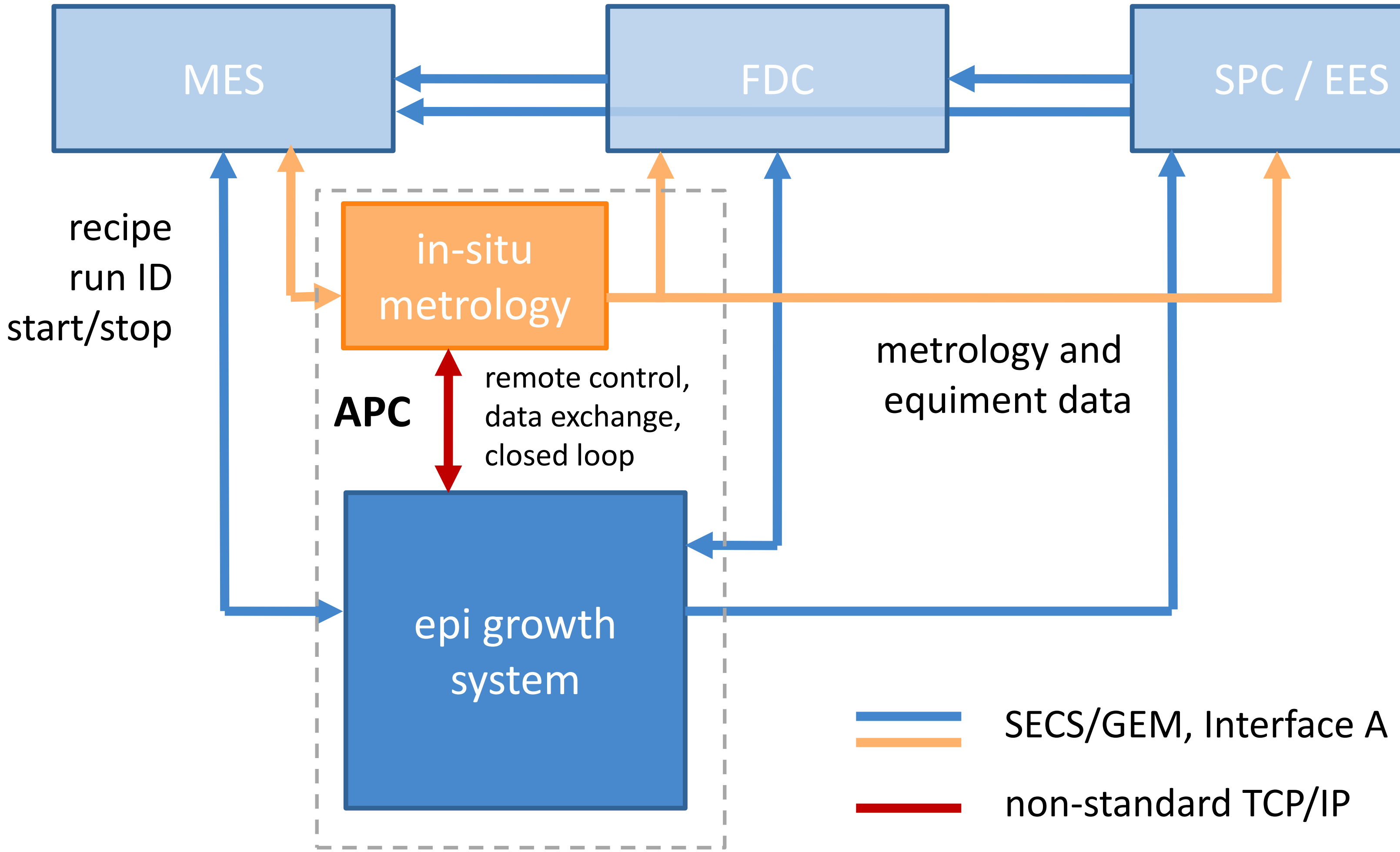


schematic courtesy of AIXTRON SE



- real-time control loop based on susceptor temperature
- additional offset correction based on wafer temperature measurement

Integration and communication

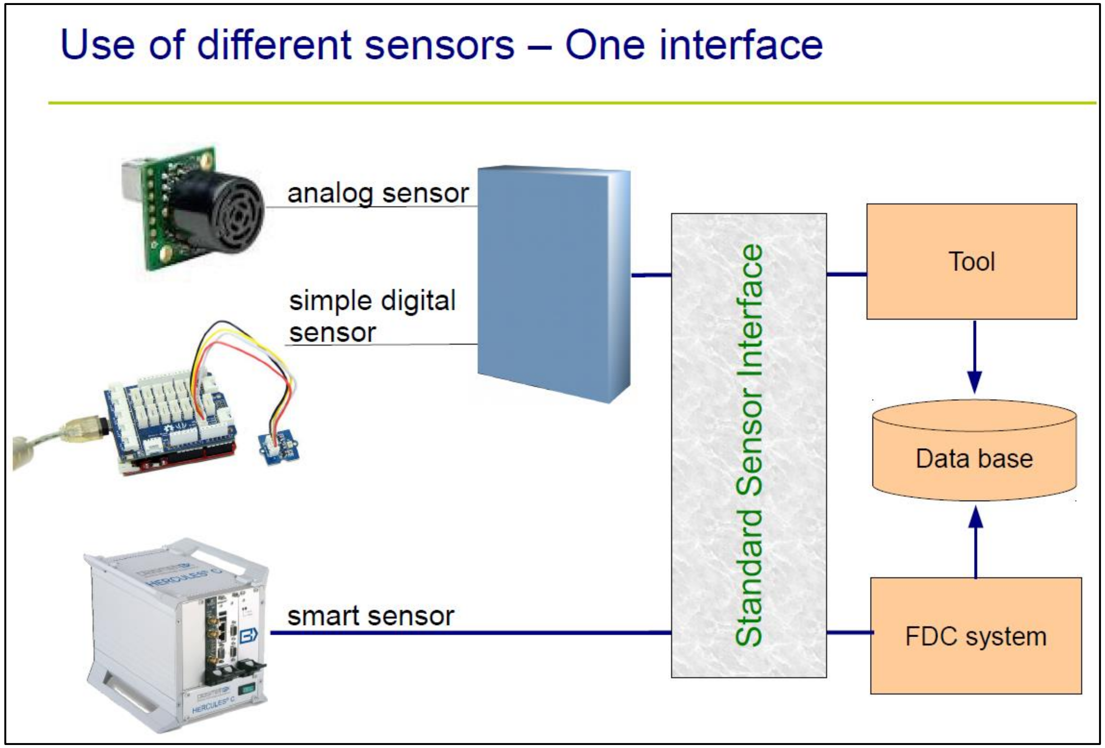


Knowledge is key

Communication standard for metrology?

SEMI Draft Document 5274G

REVISION TO ADD A NEW SUBORDINATE STANDARD: SPECIFICATION FOR SENSOR/ACTUATOR NETWORK SPECIFIC DEVICE MODEL OF A GENERIC EQUIPMENT NETWORKED SENSOR (GENSen) TO SEMI E54-0413, SENSOR/ACTUATOR NETWORK STANDARD



... sounds like a good idea!

from:
Michael Klick and Dirk Suchland, **15th European Advanced Process Control and Manufacturing Conference,** 13. -15. April 2015,

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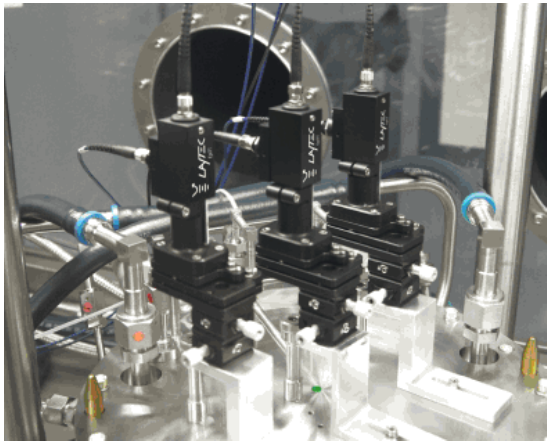
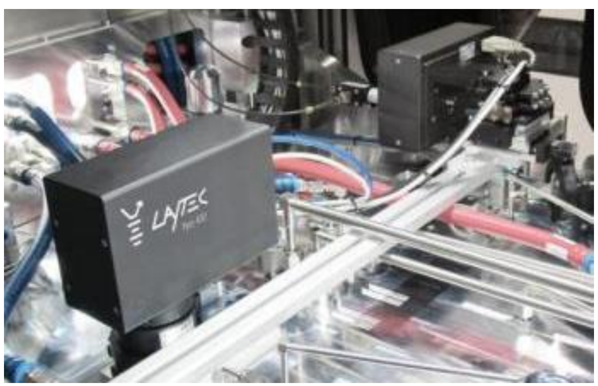
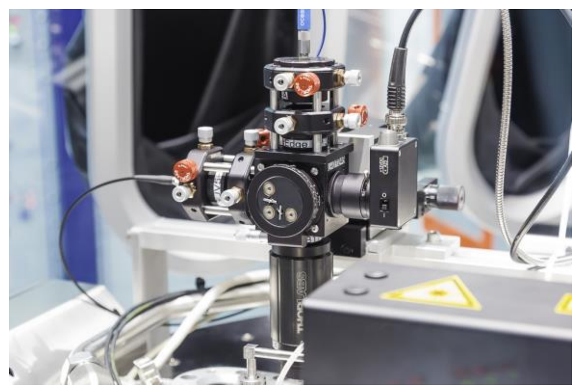
In-situ metrology techniques for CS epitaxy



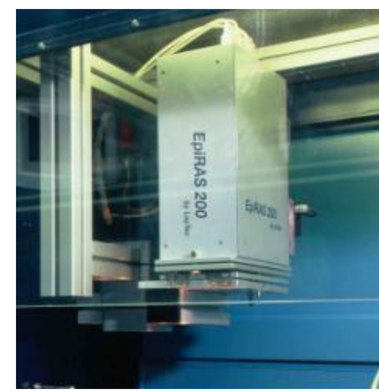
Multiple position temperature, reflectance and curvature



UV pyrometry and curvature



In-situ photoluminescence



Reflectance Anisotropy Spectroscopy (RAS)

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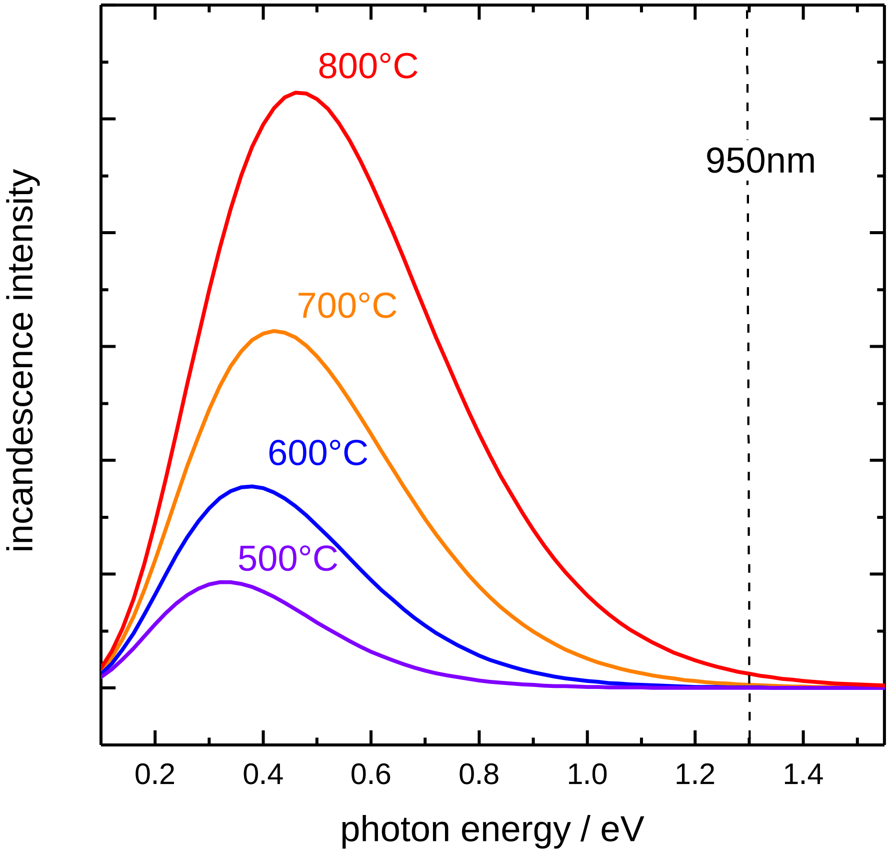
Temperature: Principle of pyrometry



Planck's equation:

$$L = \varepsilon \cdot \frac{2}{h^4 c^3} \cdot \frac{(\hbar\omega)^5}{e^{\hbar\omega/k_B T} - 1}$$

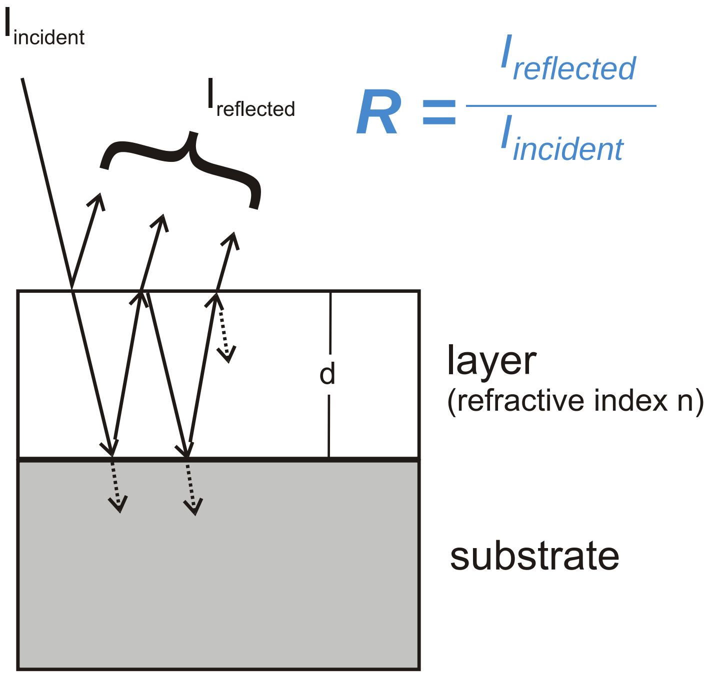
Intensity of emission or incandescence from heated black body is correlated to its temperature.

But emission of real body (wafer) is different from black body, so emissivity ε has to be determined in-situ

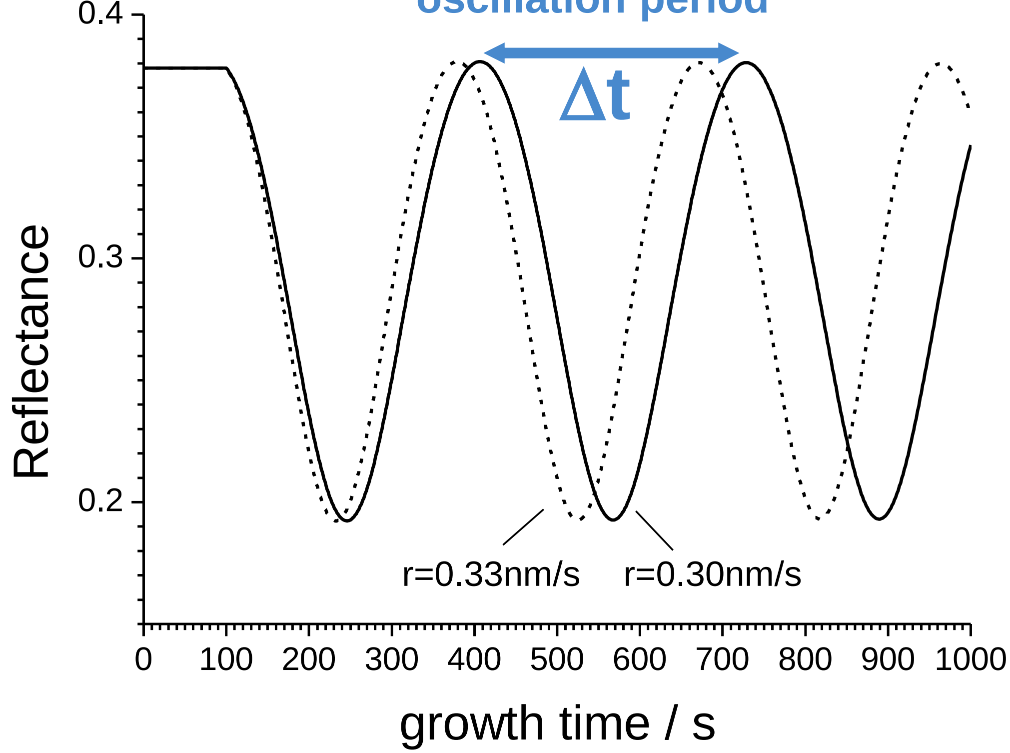
M. Planck, Verh. Dtsch. Phys. Ges. Berlin, 2 (1900) 202 and 2 (1900) 237.

Knowledge is key

Reflectance – the effect of growth rate



$$R = \frac{I_{reflected}}{I_{incident}}$$



$$\text{growth rate } r = \frac{\lambda / n}{2 * \Delta t}$$

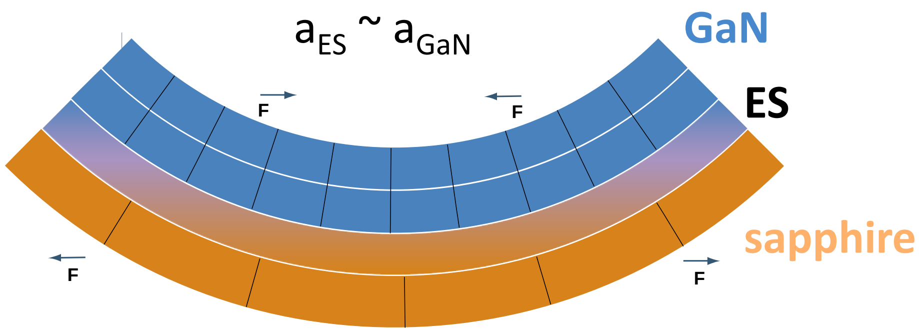
long oscillation period Δt = small growth rate r
and vice versa

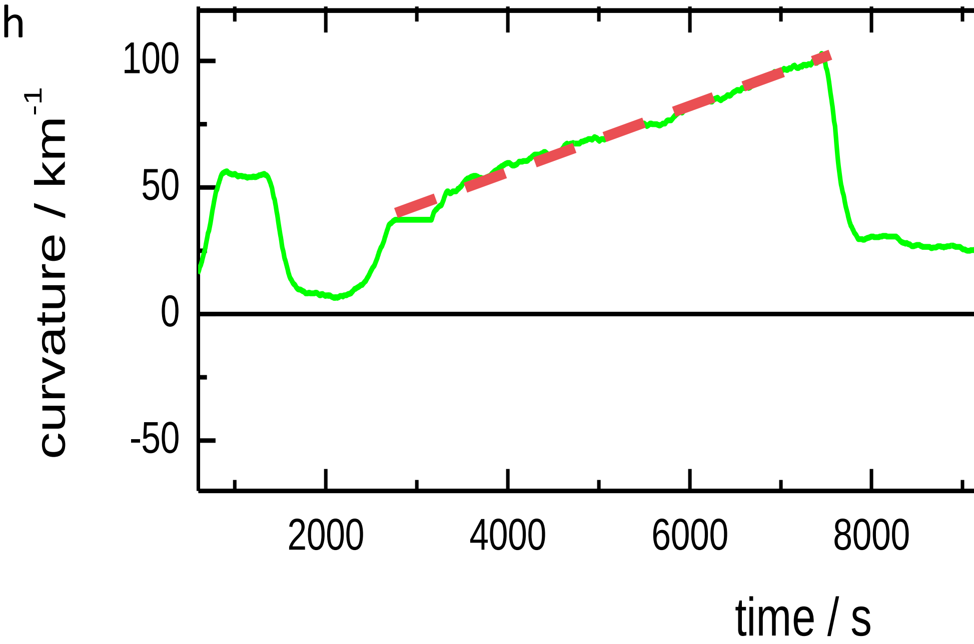
Knowledge is key

Lattice constant

- Strained growth due to lattice mismatch in hetero-epitaxy
- Curvature is linear with thickness
- Stoney formula is valid:

$$\left[\frac{1}{R_C}\right]_{Stoney}^{\frac{\Delta a}{a_s}} = \frac{6M_f}{M_s h_s^2} \bullet h_f \bullet \frac{\Delta a}{a_s}$$





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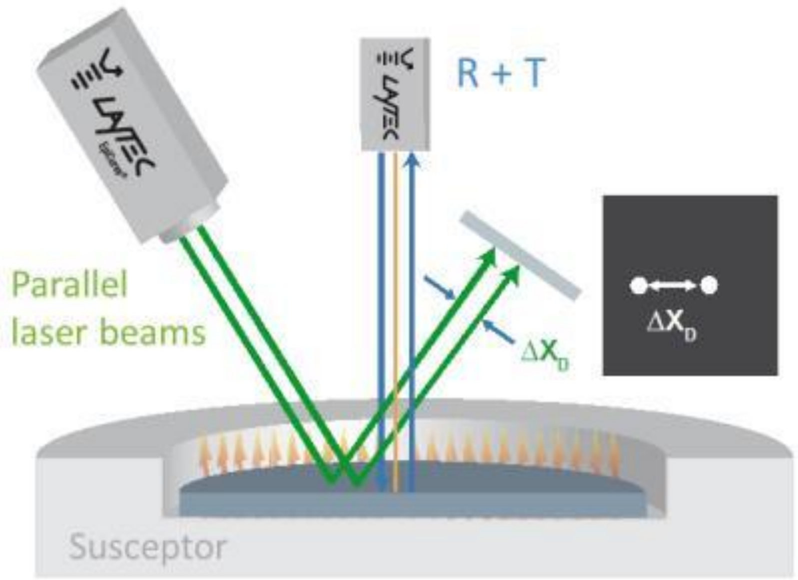
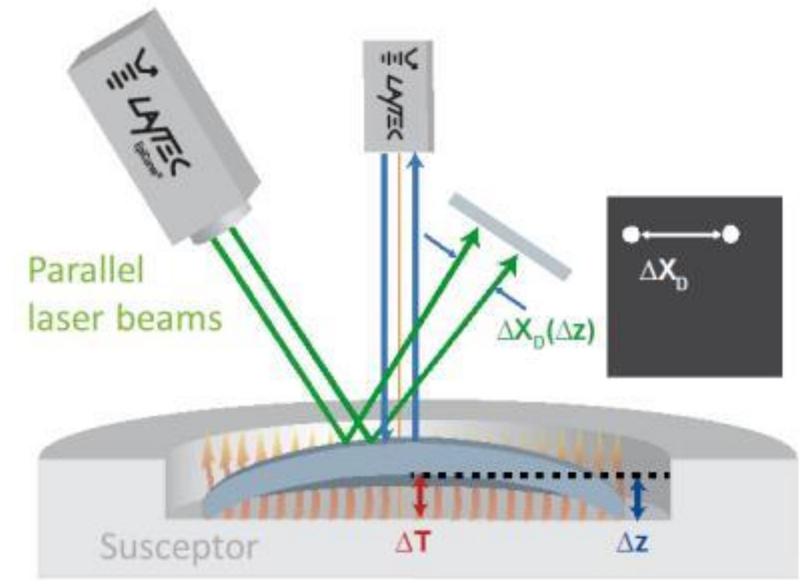
In-situ wafer bow measurement - how does it work?



Plane substrate



Bowed wafer

- Measures wafer curvature and wafer bow
- With „advanced resolution feature“ also aspherical bow is measured = early warning of plastic deformation and cracking

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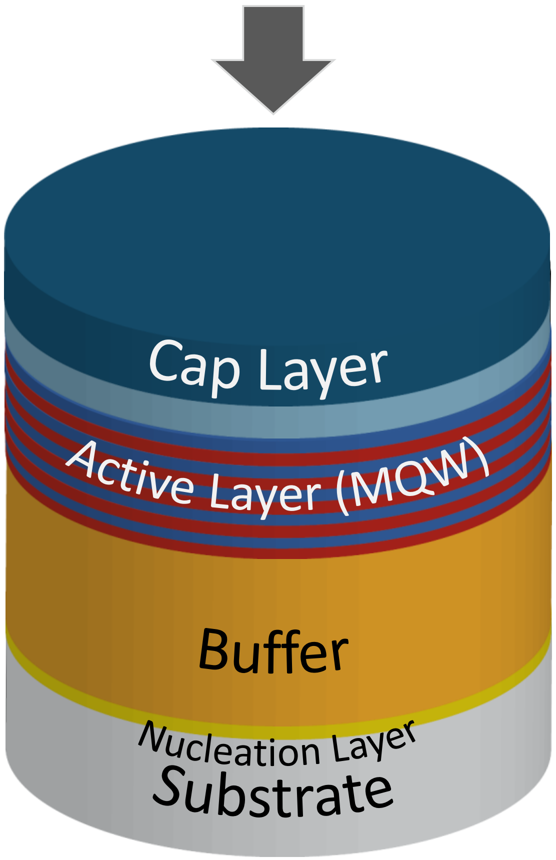
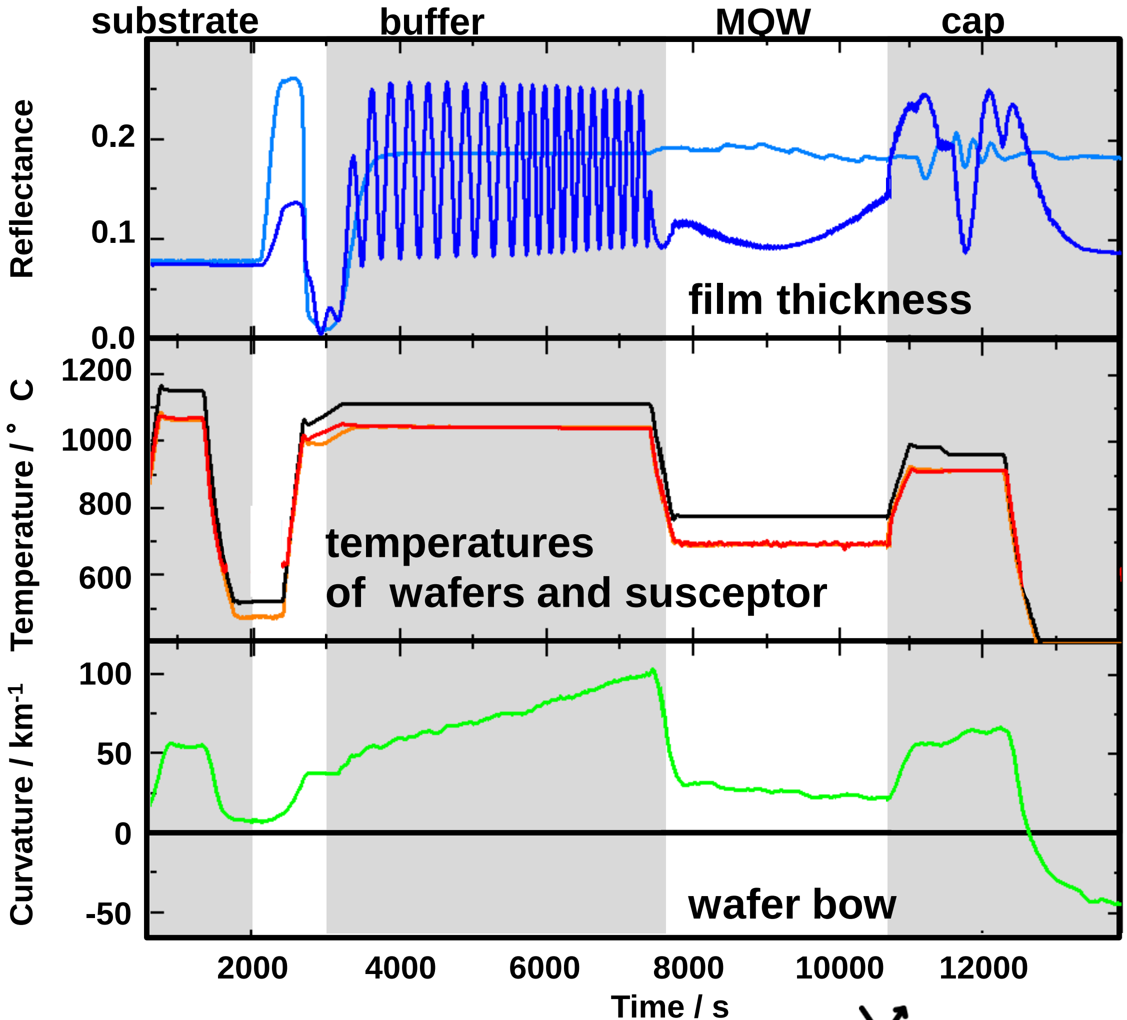
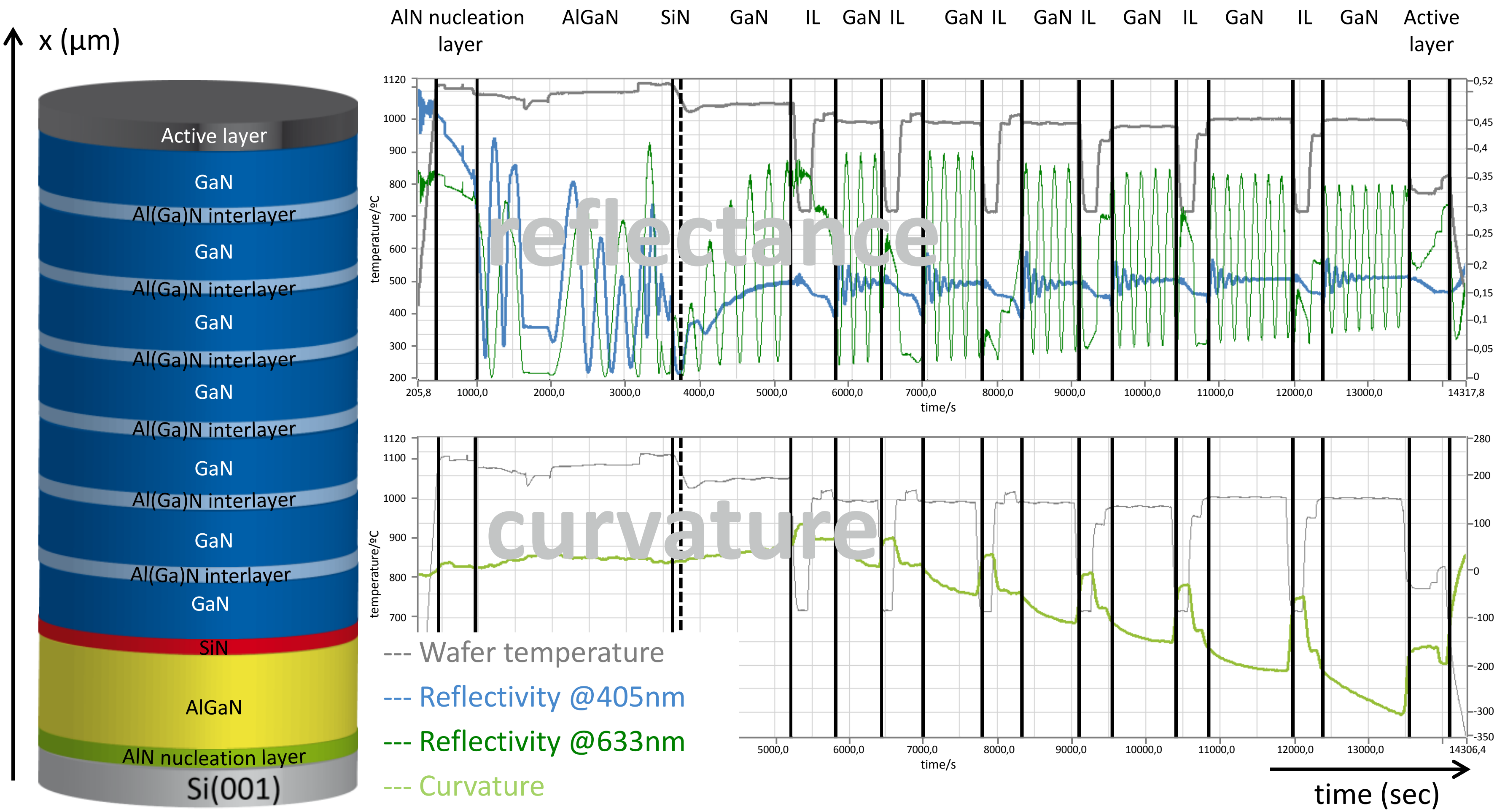
LED structure – in-situ fingerprint

LED cross section





GaN HEMT structure – in-situ fingerprint



Metrology, equipment health monitoring and more...

What in-situ metrology can provide

Product properties / Process data

Reflectance … roughness/thickness/growth rate/composition
Curvature … wafer bow/strain
Photoluminescence … ternary composition
Wafer temperature

Equipment data

Wafer and/or carrier rotation frequency
Carrier temperature
Wafer-to-ceiling gap

Critical events

Wafer flipping
Wafer cracking

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From Data to Information

primary measured data
e.g. Reflectance, Temperature, Curvature, Photoluminescence etc.

+

process knowledge + software algorithms
e.g. which material was grown?
how to interpret?
optical constants ...

high level information
e.g. growth rate, layer thickness, roughness, strain, LED emission wavelength

→ much more valuable data for APC

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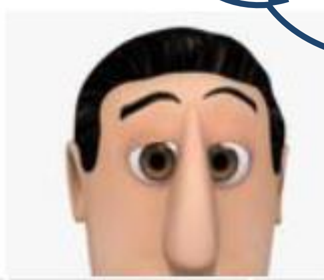
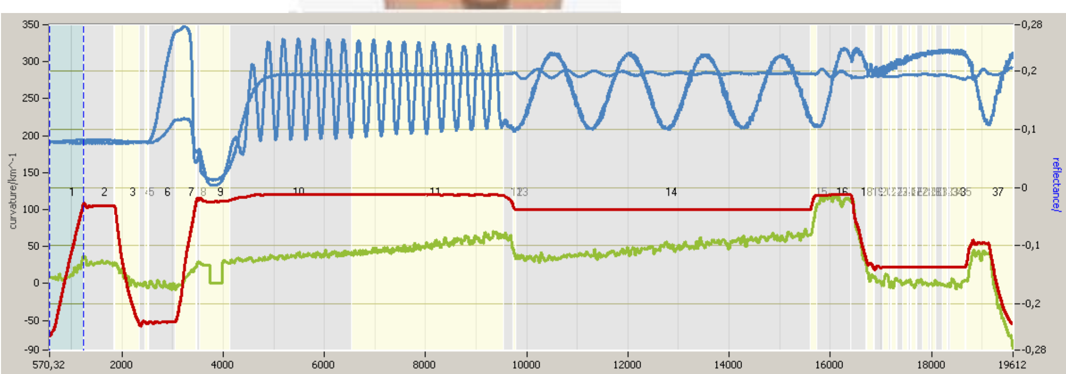
Data ...

Multi wafer data analysis is complicated ...





example:
6 traces per wafer
x 14 wafer
x 2 radial positions
= 168 curves ...

Moe, the MOCVD Manager at an LED FAB (courtesy of Rudolph Technologies)

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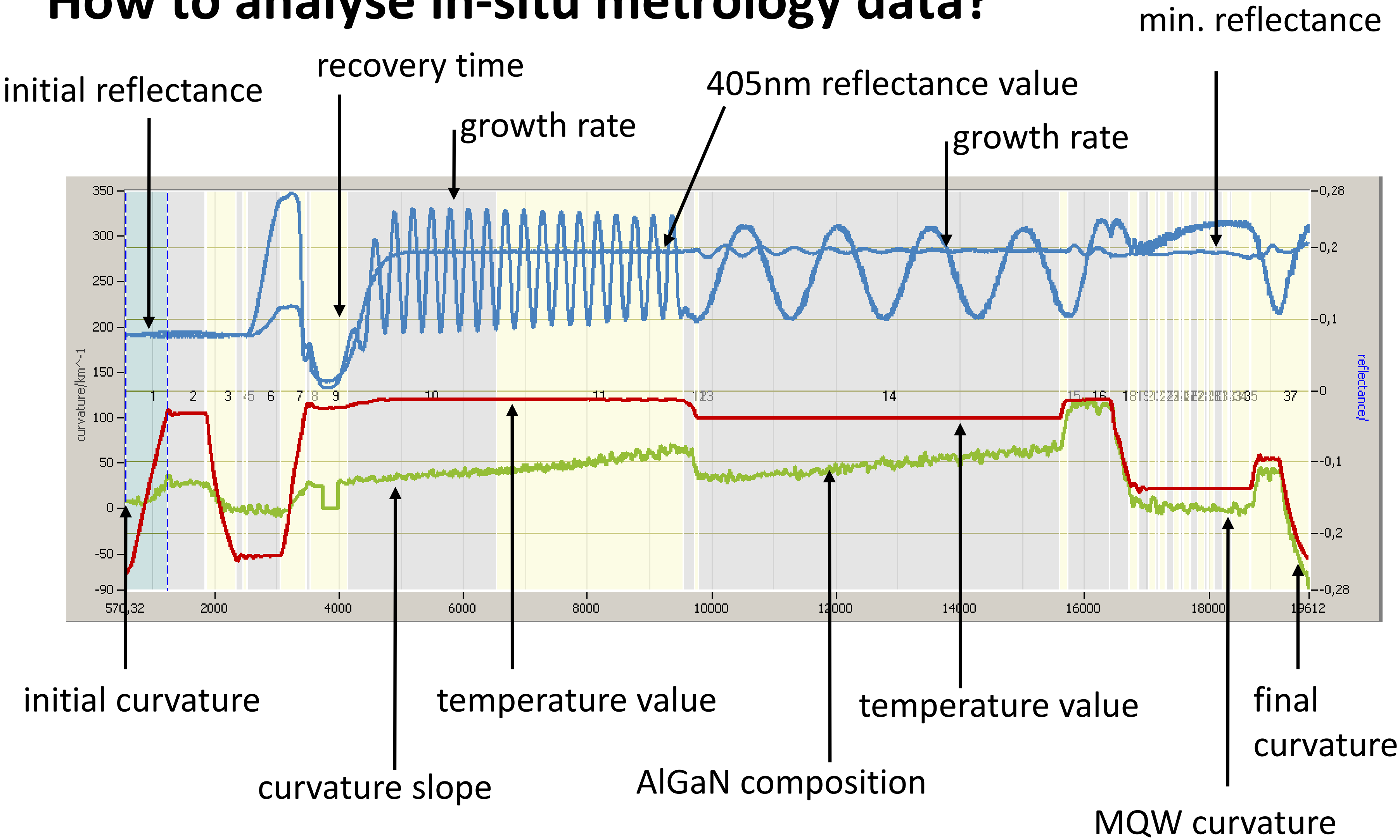
How to analyse in-situ metrology data?



Communication with tool allows synchronization to process steps

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APC by means of in-situ data

- Data complexity is reduced by applying advanced analysis on the raw data
- Multiple single analyis steps are combined into one analyis recipe:

All steps | Layer thickness unit: nm/s

Position	StepCount	Begin	End	AnalysisName	State	Result	Check	Comment
1	11	6539,52	9539,17	NKR Free Fit	✓	R=0,663 nm/s	☑	
2	14	9789,65	15604,19	NKR Fix Fit	✓	R=0,136 nm/s	☑	
3	14	9789,65	15604,19	Basic\DataProcessing	✓		☐	
4	11	6539,52	9539,17	Basic\Average	✓	Average=0,173	☑	
5	10;14	0	0	Composition: AlGaN, InGaN	✓	composition x=0,059	☑	

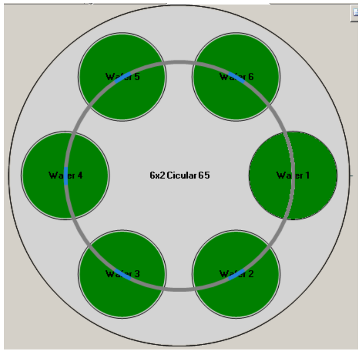
(grey ✓) analysis successful, no specs defined

(green ✓) analysis successful, result in spec

(red ↓) (red ↑) analysis result of out spec

→ wafer is ✓ if every step is ✓

→ run is ✓ if every wafer is ✓



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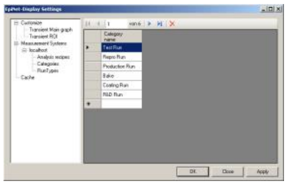

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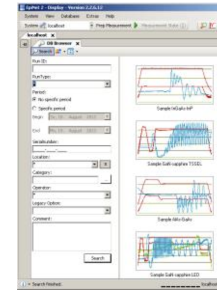
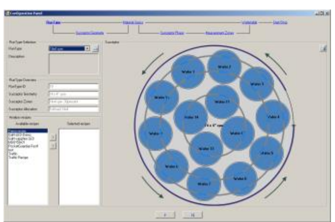
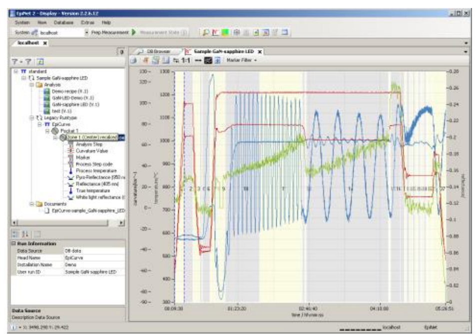
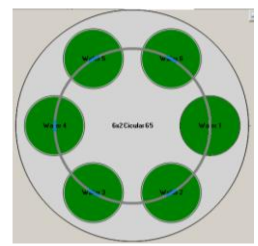
4	11	6539,52	9539,17	Basic\Average	✓	Average=0,173	☑	
5	10;14	0	0	Composition: AlGaN, InGaN	✓	composition x=0,059	☑	

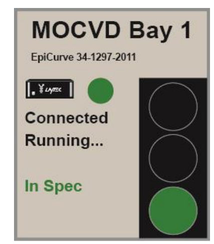


Prepare run → Start run → Data display → Analysis during run → Smart visualization → Export to MES









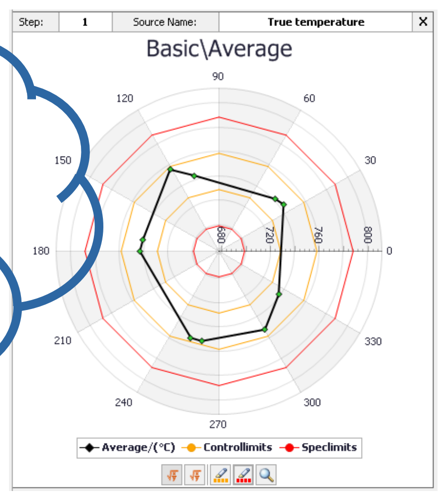
Knowledge is key

Information!

Simplification

Integration

Visualization



That's much better!

Moe, the MOCVD Manager at an LED FAB (courtesy of Rudolph Technologies)

... requires process knowledge!

LAYTEC Knowledge is key

Outline

Introduction
– Two semiconductor industries
– Types of metrology

In-situ metrology and control in Compound Semiconductor Epitaxy
– Integration of metrology
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– From data to information
– Application examples

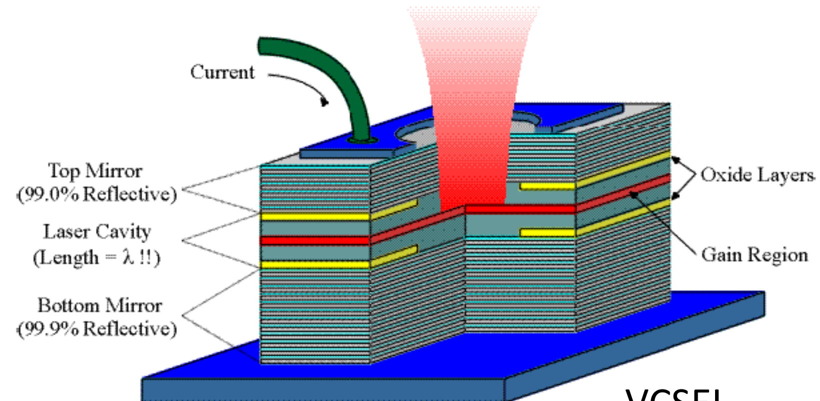
Opportunities for in-situ metrology and control in Si Semiconductor Industry

Summary

LAYTEC Knowledge is key

Example: Cost reduction in GaAs foundry

- Foundry business:
  - Many growth systems
  - Many different structures
  - Different wafer configurations
  - Different wafer sizes ...



VCSEL

- Some device structure consists of >100 layers
- Including several ternary layers with different compositions
- Recalibration of process parameters needed after reactor maintenance (~1x per month)

Example: Cost reduction in GaAs foundry II

Status quo before optimization

- Recalibration of process parameters needed after maintenance
- Ex-situ characterization of ternary composition and layer thickness not possible on complex multi-layer device stack
- Special calibration structure to be grown after reactor maintenance
- Ex-situ SIMS characterization after run

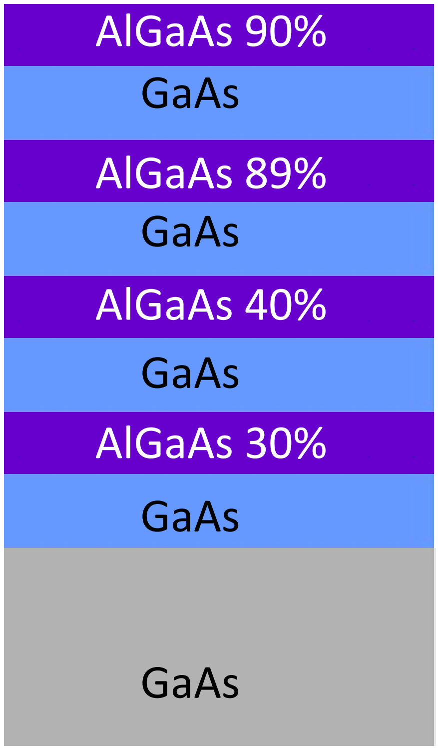
→ additional costs and additional MOCVD down time (waiting for results)

Goal

- Replace ex-situ metrology during recalibration cycle by in-situ metrology
- Savings: More uptime of MOCVD = higher productivity

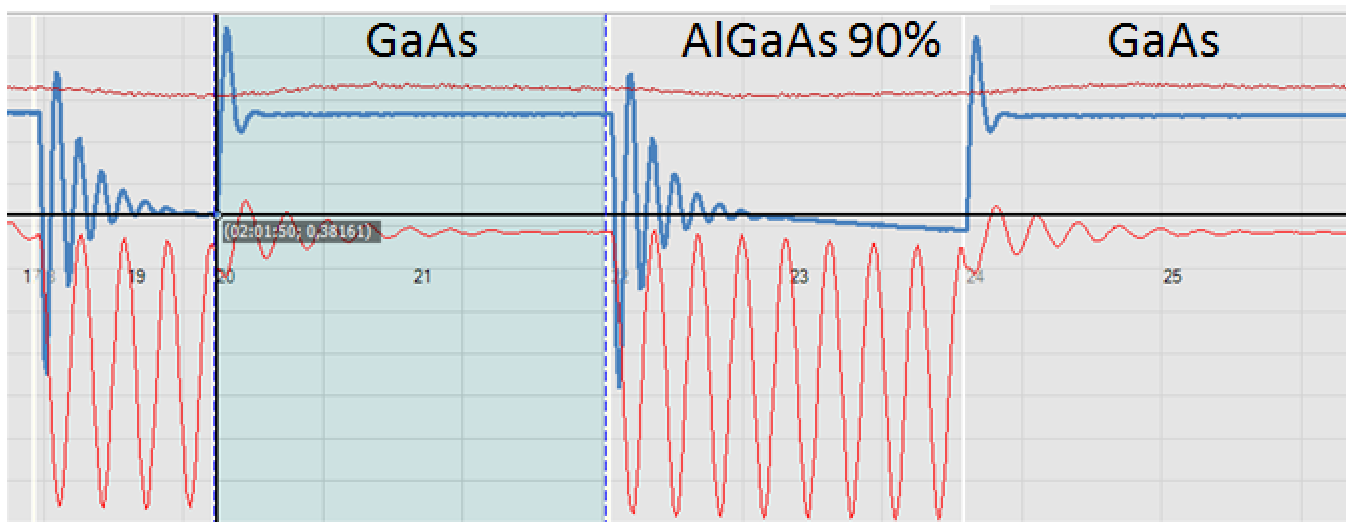
LAYTEC Knowledge is key

Example: Cost reduction in GaAs foundry III



← calibration structure for VCSEL process

↓ in-situ measured reflectance data



- In-situ reflectance data are (automatically) analyzed
- growth rate and ternary composition are provided as fit results at the end of the run

LAYTEC Knowledge is key

Example: Cost reduction in GaAs foundry IV

Material	x (goal)	Step	in-situ fit	Offset	ex-situ SIMS
$Al_xGa_{1-x}As$	40%	15	**43,5%**	0,5%	43%
$Al_xGa_{1-x}As$	40%	11	**42,6%**	0,4%	43%
$Al_xGa_{1-x}As$	30%	7	**35,1%**	1,6%	33,5%
$Al_xGa_{1-x}As$	30%	3	**31,7%**	1,8%	33,5%
			Average:	**1,1%**	

- Customer requirement of 1% accuracy throughout the calibration structure was achieved
- in-situ calibration scheme proved to be as accurate as traditional ex-situ calibration scheme, but saves time
- Aditionally: For HEMT and HBT fit also works on real device structures making calibration run completely superfluous

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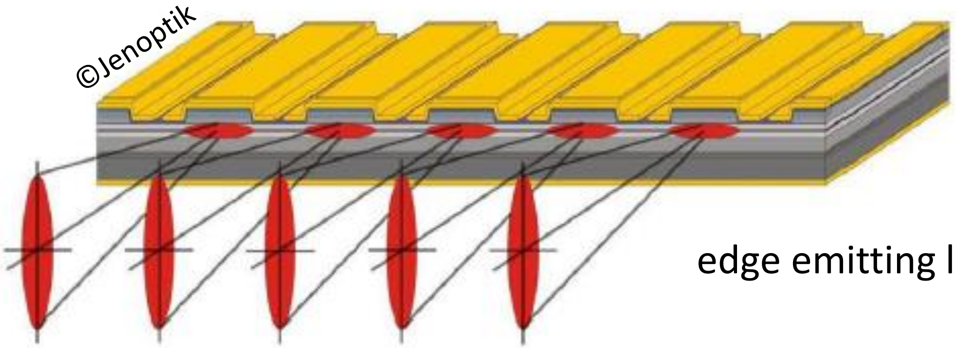
LAYTEC Knowledge is key

Example: SPC at Jenoptik Diode Labs

- Growth of edge emitting laser structures on GaAs wafers
- Routine calibration of $Al_xGa_{1-x}As$ composition and growth rate
- comparison with ex-situ XRD
- in-situ measured temperature and growth rate data are transfered into MES system for SPC

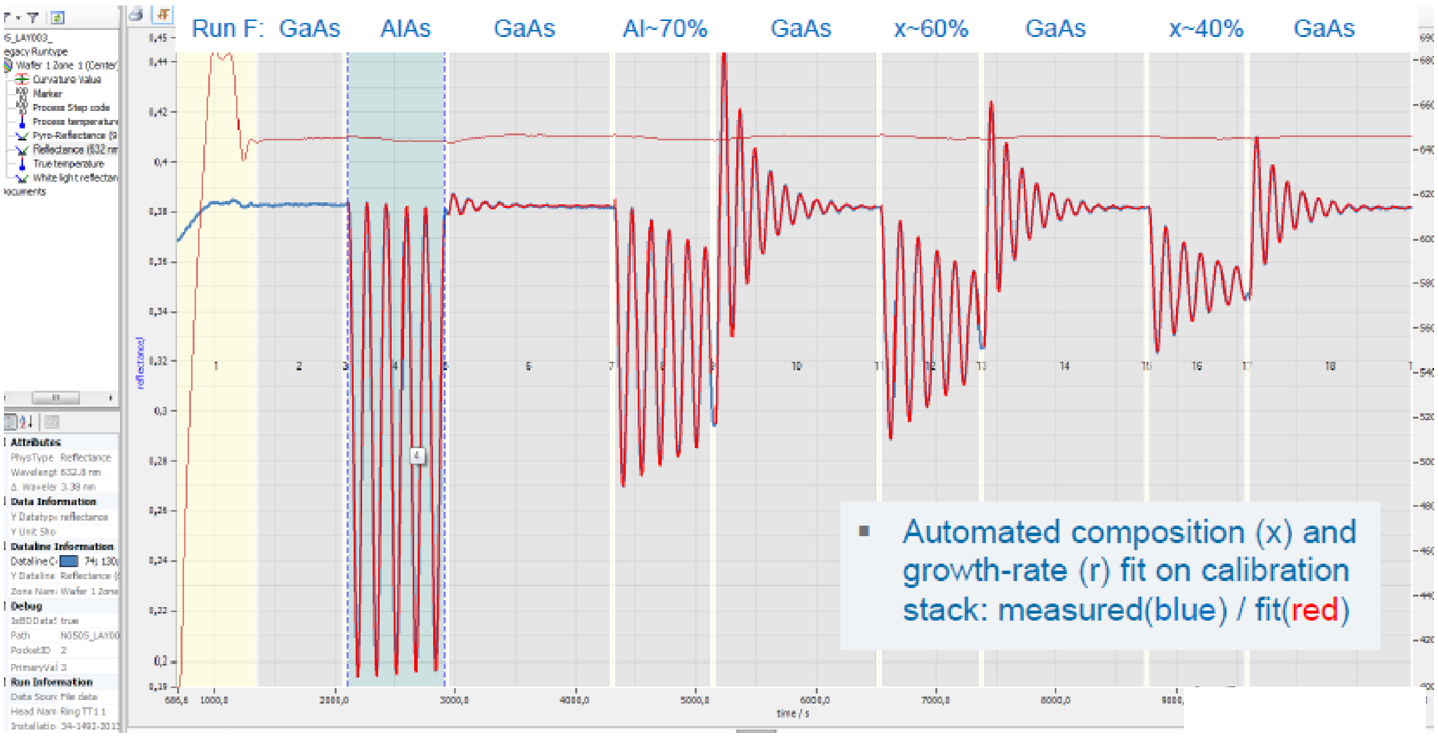


edge emitting laser

Knowledge is key

Example: SPC at Jenoptik Diode Labs II

Routine AlGaAs process calibration by in-situ reflectance



In-situ reflectance data (blue) and fitted curves (red) overlay well

Knowledge is key

Example: SPC at Jenoptik Diode Labs II

Comparison ex-situ vs.in-situ analysis

Run F	Target		ex-situ XRD		in-situ	in-situ	in-situ	in-situ
Layer	d (nm)	x	r (nm/s)	x	r(nm/s)	x	Δr/r	Δx
GaAs	750	0,000	0,5971	0,000	0,602	0,002	0,8%	0,2%
Al(0,4)GaAs	450	0,400	0,5531	0,402	0,564	0,402	2,0%	0,0%
GaAs	750	0,000	0,5964	0,000	0,602	0,000	0,9%	0,0%
Al(0,6)GaAs	450	0,600	0,5659	0,601	0,558	0,607	-1,4%	0,6%
GaAs	750	0,000	0,5959	0,000	0,600	0,000	0,7%	0,0%
Al(0,7)GaAs	450	0,700	0,5828	0,695	0,577	0,690	-1,0%	-0,5%
GaAs	750	0,000	0,5967	0,000	0,599	0,000	0,4%	0,0%
AlAs	450	1,000	0,5890	1,000	0,598	1,000	1,5%	0,0%
GaAs-Sub.		0,000						

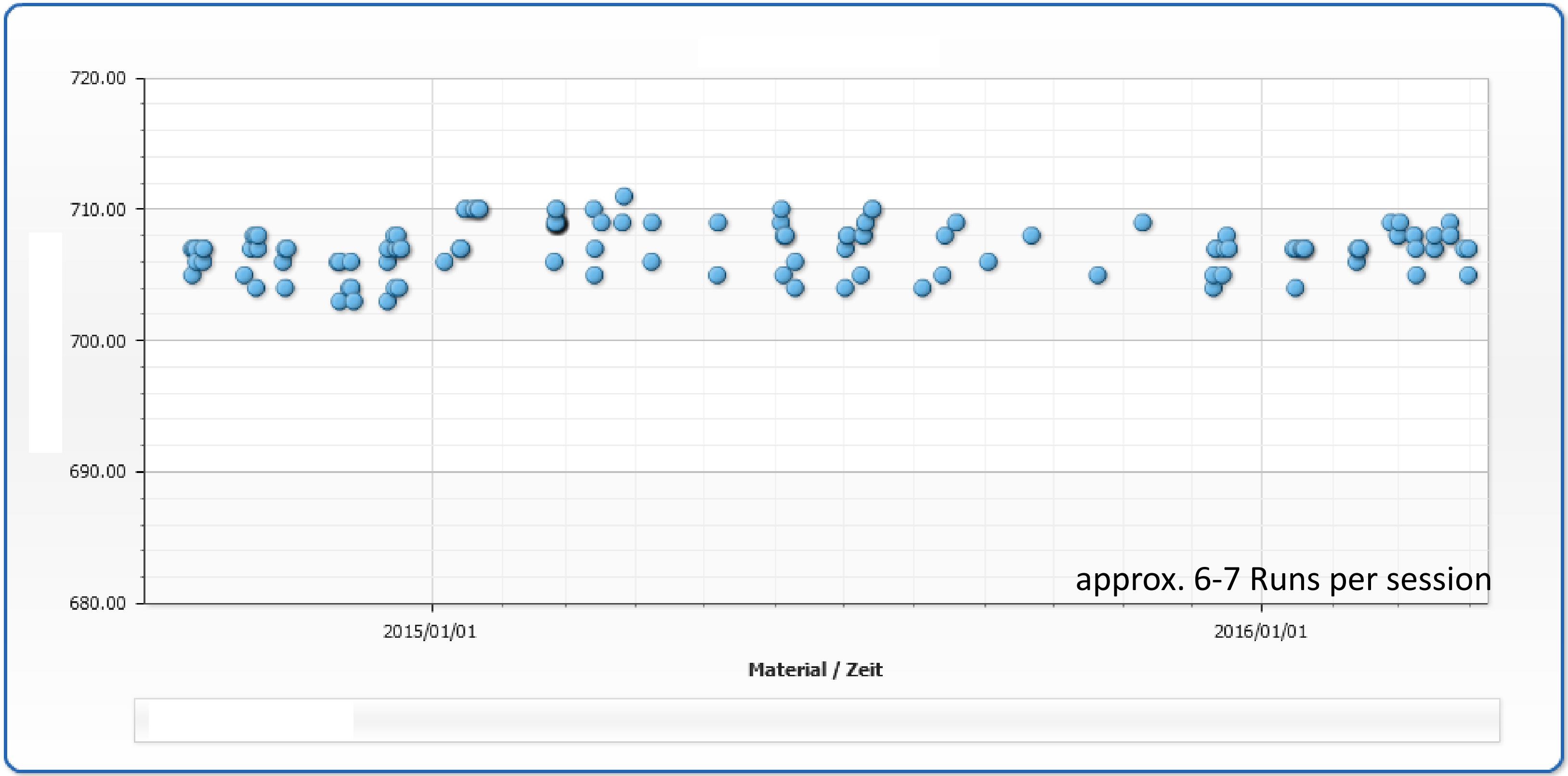
Single wavelength in-situ reflectance analysis (633nm) gives:

- AlGaAs composition with accuracy of ±0.5%
- growth rates with ±1% variation from XRD

Example: SPC at Jenoptik Diode Labs III

Statistic Process Control by MES

Temperature of #Layer1 over last 1,5 years measured by EpiTT

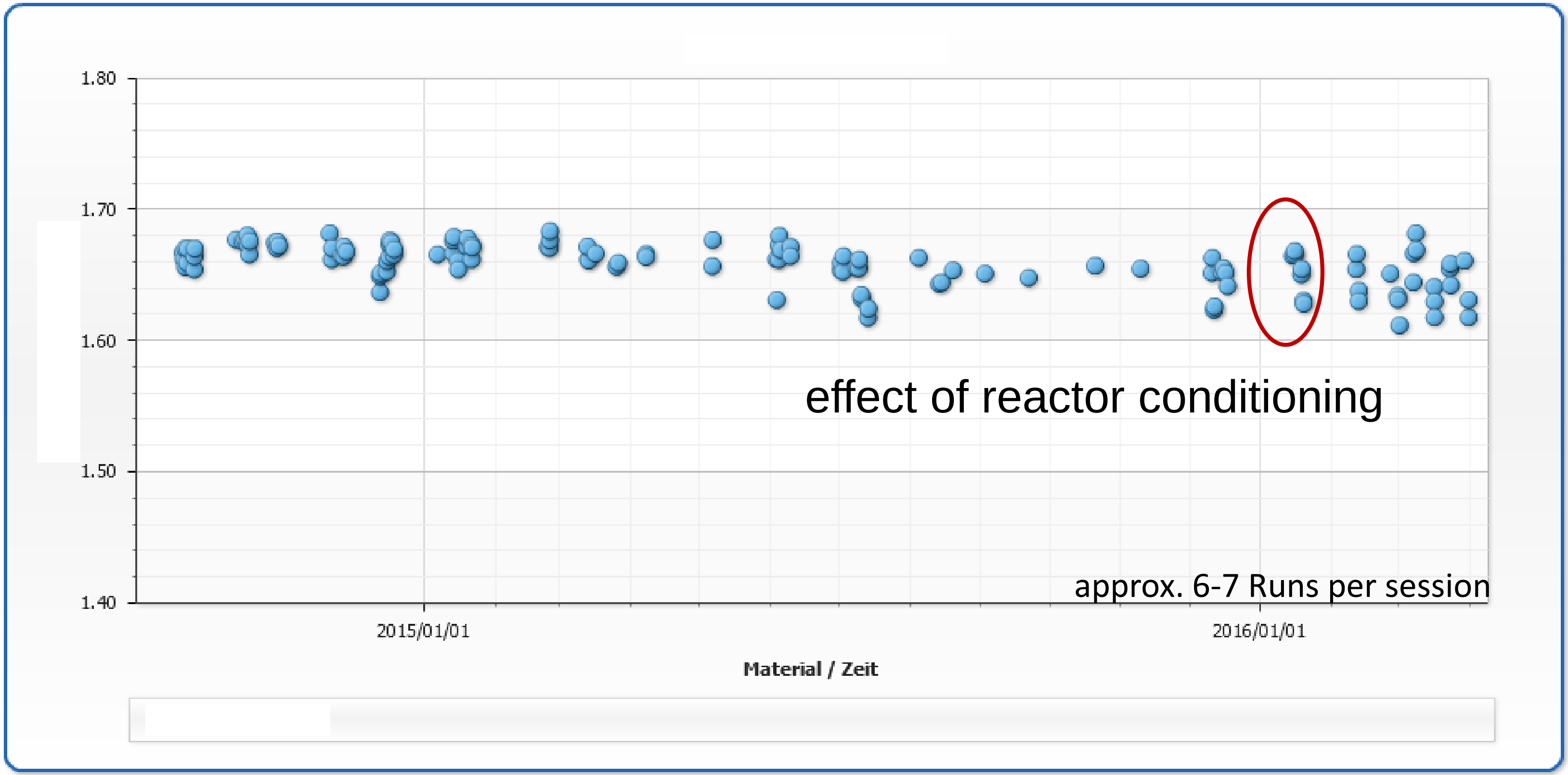


data courtesy of M. Zorn, Jenoptik

Example: SPC at Jenoptik Diode Labs IV

Statistic Process Control by MES

Growth rate of #Layer1 over last 1,5 years measured by EpiTT



data courtesy of M. Zorn, Jenoptik

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LAYTEC Knowledge is key

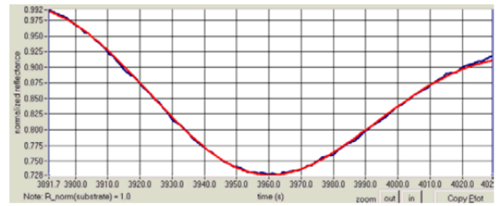
Example: SPC at Kopin / IQE MA

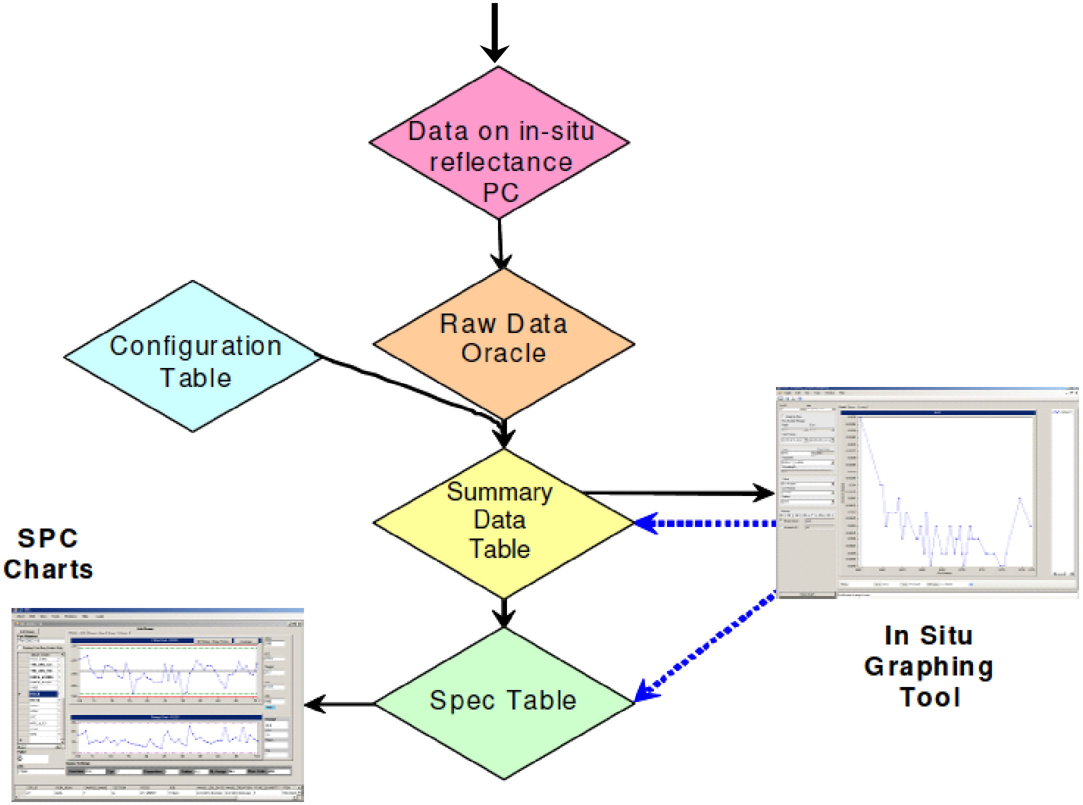
- Kopin/IQE MA is manufacturer of transistor-epiwafers (BiHEMT, BiFET, HBT, pHEMT)
- In-situ reflectance measurement during epi-layer growth gives data for every epi-layer on every wafer - as it is grown
- Xray diffraction, photoreflectance and photoluminescence can also provide detailed epi-layer information, however it is available only after long delay from the growth; this is problematic to achieve sufficient throughput
- Without in-situ data, layer thickness can be checked only through limited destructive testing and/or special calibration runs

M. Youngers, P. Rice, G. Yeboah, E. Rehder, O. Laboutin, K. S. Stevens, and W. Johnson
Kopin Corporation, now IQE MA
CS MANTECH Conference, April 23rd - 26th, 2012, Boston, Massachusetts, USA

Example: SPC at Kopin / IQE MA II

in-situ measured reflectance data (blue) and fit (red) are used to determine growth rates etc.

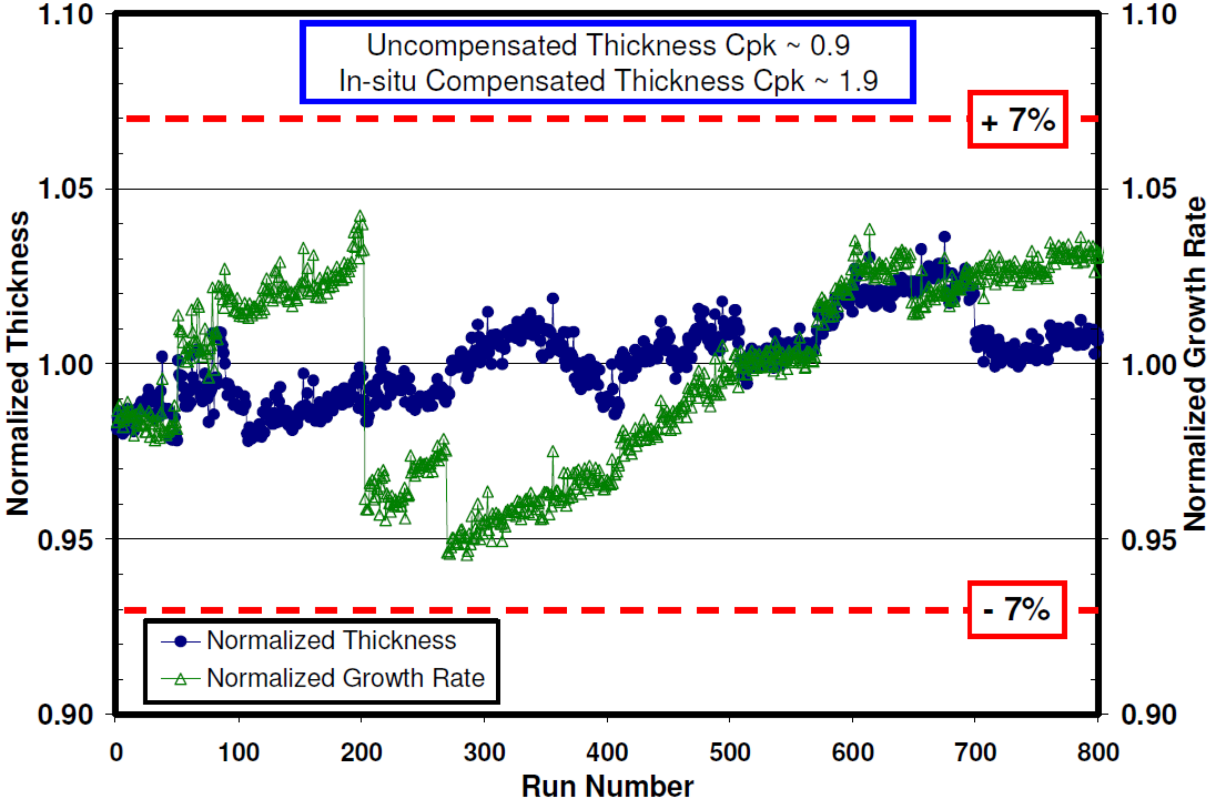




Knowledge is key

Example: SPC at Kopin / IQE MA III

Growth rate data



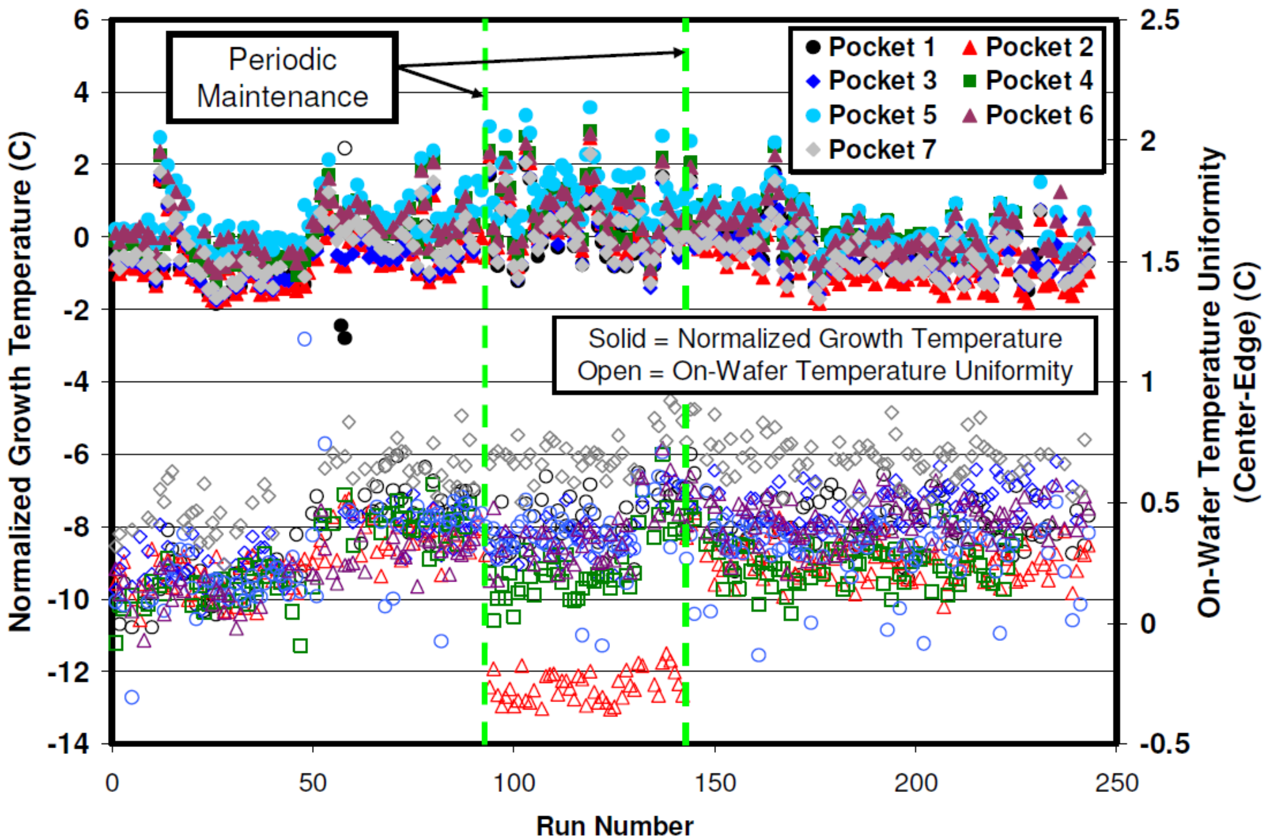
- Small growth rate drifts (due to reactor coating) and shifts (due to reactor maintenance) are visible
- w/o in-situ data layer thickness C_{pk}~0.9 might be expected versus a +/-7% thickness spec
- with in-situ production data, layer thickness can be monitored with 100% visibility such that C_{pk}>1.7 is easily obtained

- in-situ growth rate data enhances epi layer thickness control during production
- provide the ability to correct when necessary.

Knowledge is key

Example: SPC at Kopin / IQE MA IV

Wafer temperature data



- average surface temperature and on-wafer temperature uniformity during growth for ~250 runs (~1,750 wafers)
- can be readily compared before and after reactor maintenance
- a subtle difference (~0.5K) in the on-wafer temperature uniformity of pocket 2 relative to the other pockets is evident as a function of routine periodic maintenance

Knowledge is key

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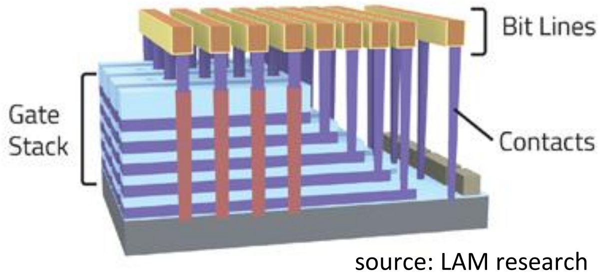
Summary

LAYTEC Knowledge is key

New devices, more complex growth …

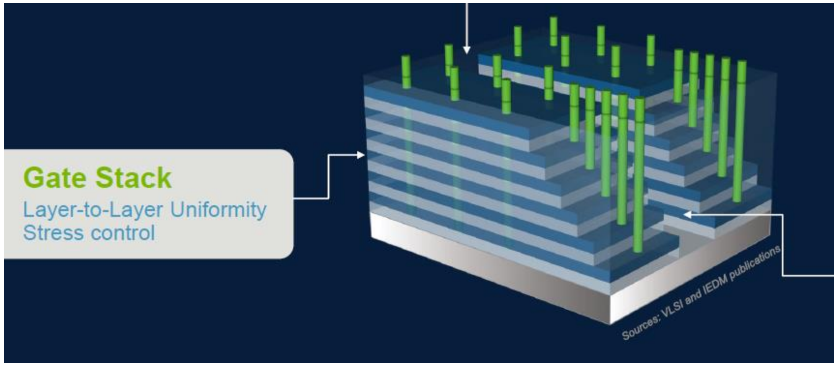
Example: **3D-NAND** memory structures

- consist of 20 … >100 layers
- e.g. 48 pairs of SiO and SiN
- are grown in cluster tools on 4x300mm wafers
- require tight control of layer thickness and strain
- cannot easily characterized after growth
- ideal application for optical in-situ metrology ...



source: LAM research

source: Applied Materials talk on Semicon West 2015



LAYTEC Knowledge is key

In-situ monitoring of 3D-NAND growth in PECVD

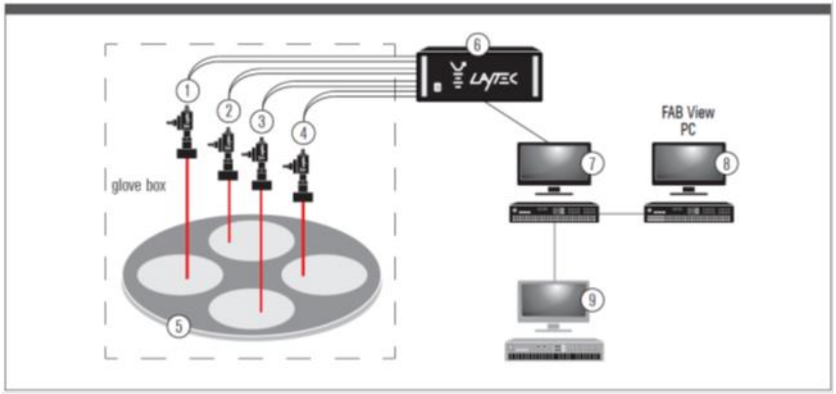
- Installation at TU Ilmenau
- Oxford Instruments ICP-CVD-Plasmalab 100 (ICP-PECVD)
- Single wafer, 1 head
- Aperture: ~10mm; apertures as small as 1mm demonstrated
- Layer thickness (<20nm) in multilayer (>50) stacks at high precision

Optical head was mounted on reactor

Critical aperture can be as small as 1mm

LAYTEC Knowledge is key

In-situ monitoring of 3D-NAND growth in PECVD



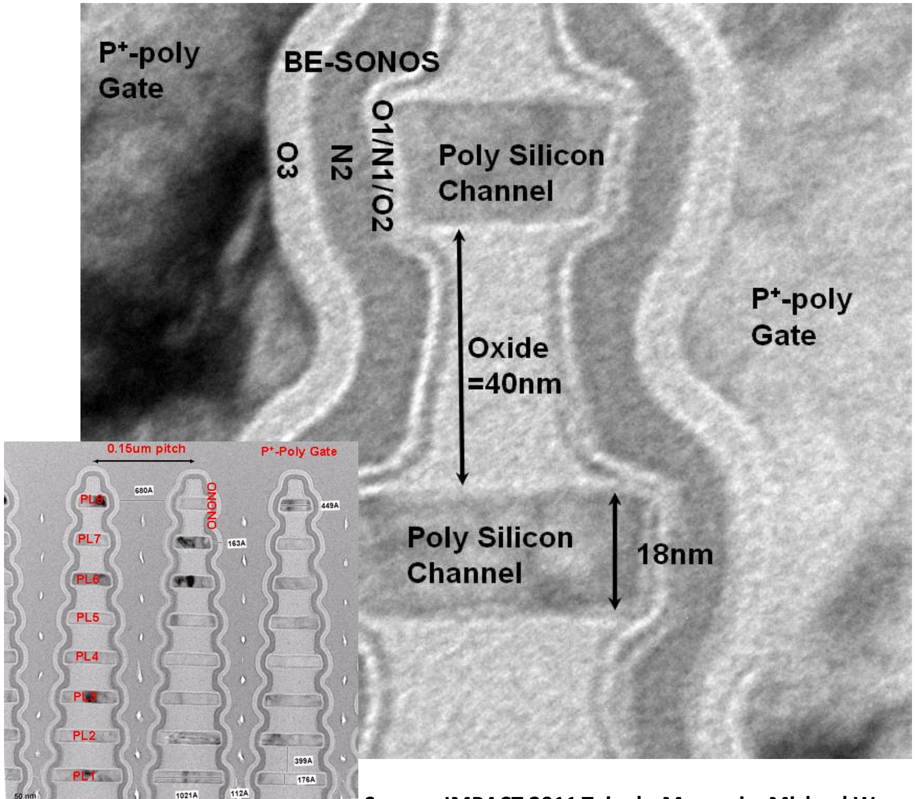
- 1-4: optical fiber heads (up to 4 heads; more planned)
- 5: Deposition chamber(s)
- 6: Electronic control unit
- 7: LayTec control computer

Single head LayTec 3DStaR was installed on chamber

4-head configuration possible

LayTec Knowledge is key

In-situ monitoring of 3D-NAND growth in PECVD



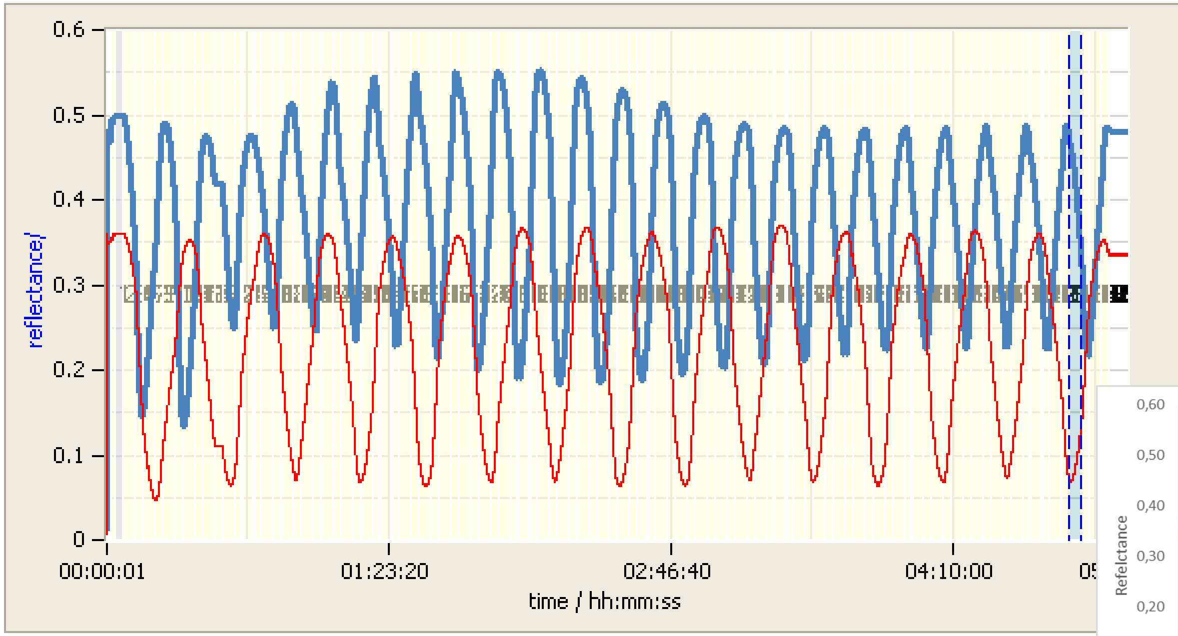
Source: IMPACT 2011 Taipeh; Macronix, Michael Wang

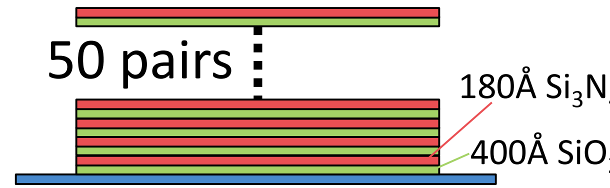
- Sample stack for 3D NAND structures was grown at IMN MacroNano @ TU Ilmenau:
  - Multilayer stack of 50 pairs of nominally 18nm of Si_xN_y and 40nm of SiO_2
- Deposition rate ~5-25nm/min

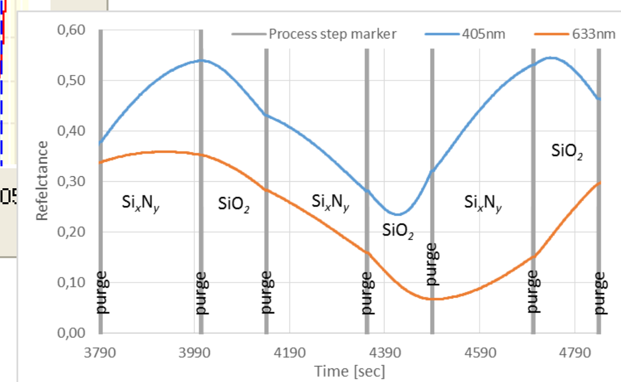
Sample structures of a published 3D NAND stack were grown as Si_xN_y/SiO_2 and Si/SiO_2 stacks.

LAYTEC Knowledge is key

In-situ monitoring of 3D-NAND growth in PECVD





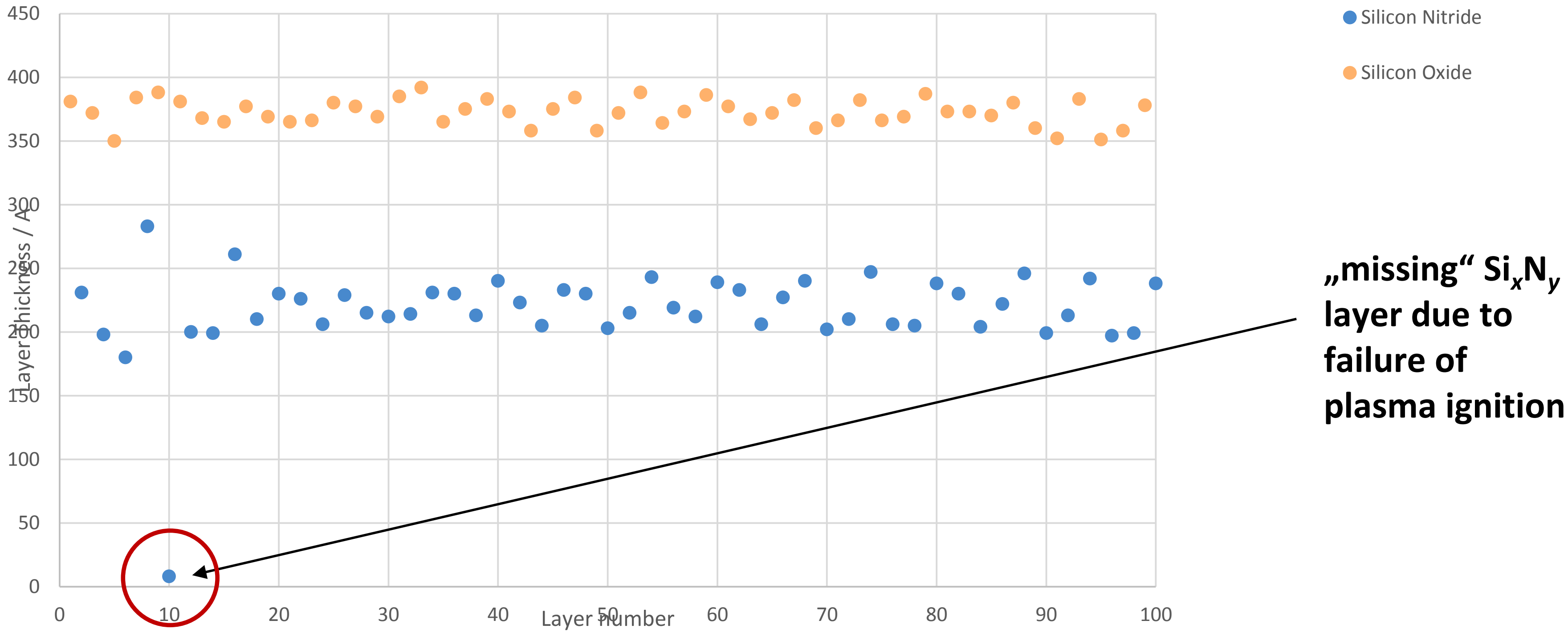


Si_xN_y/SiO_2 stack consisting of 50 layer pairs was grown. In-situ layer thickness measurements allow for individual layer thickness measurement up to precision of 5A or better.

LAYTEC Knowledge is key

In-situ monitoring of 3D-NAND growth in PECVD

Results: Layer-to-layer thickness variation

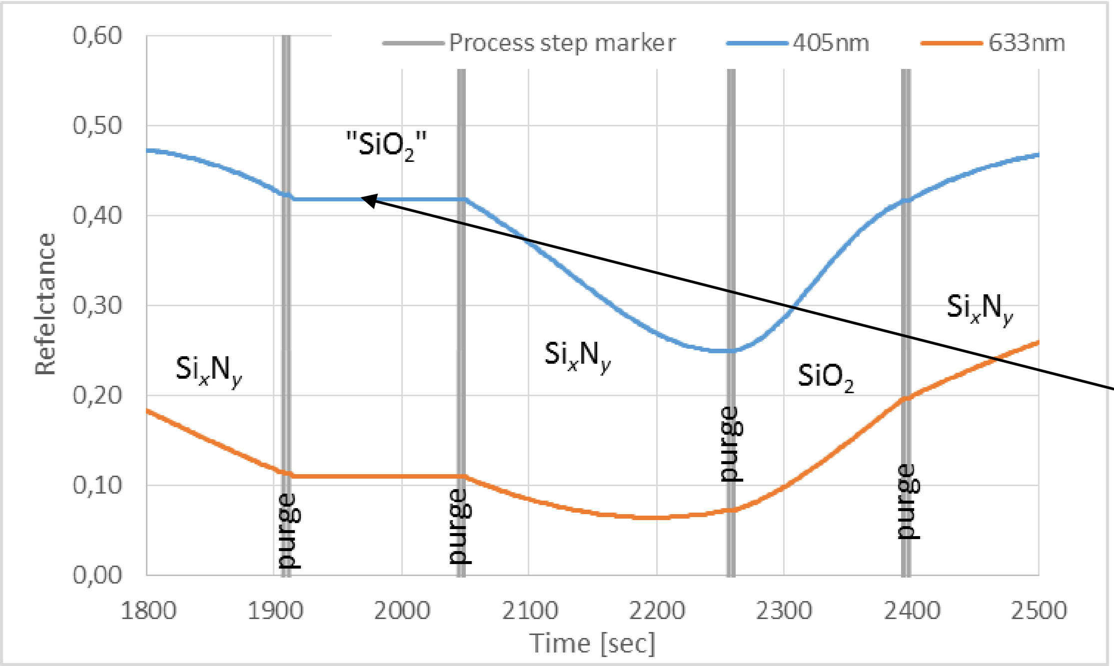


Thickness variation for Si_xN_y and SiO_2 is observed.
Thickness error usually ~5% or lower.

LAYTEC Knowledge is key

In-situ monitoring of 3D-NAND growth in PECVD

Root-cause analysis of process deviations:
Unknown growth effects revealed by 3DStaR



„missing“ SiO_2 layer due to failure of plasma ignition

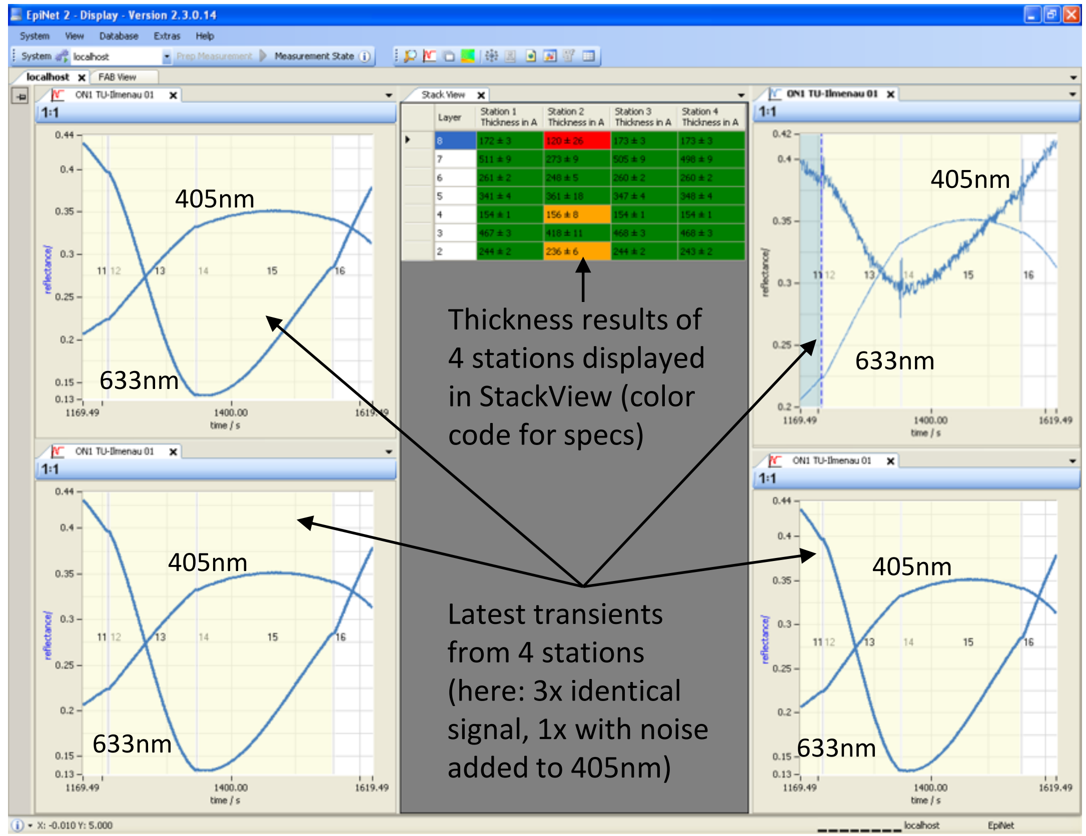
→ transients clearly show that no layer is grown

Transients allow in-situ inspection of growth processes. In particular, unforeseen and unexpected events become obvious!

LAYTEC Knowledge is key

Multi-head 3DStaR configuration

- Multi-head setup possible for:
  - Multi chamber tools
  - Multiple positions in one chamber
- StackView displays layer thickness + uncertainty in-situ for up to 4 heads
- Spec control by color



Currently 3DStaR can be equipped with 1-4 metrology heads (2 wave-lengths). 3rd wavelength/temperature measurement optional.

Compound semiconductor vs. Semi market - updated

	Compound (CS)	Traditional Semi	Advanced Semi
Wafer size	(2"), 3", 4", 6"	200/300mm, (450mm)	300mm, (450mm)
Growth run duration	~6-8 hours	~1 min	> 1 hour
Number of layers per run	~20...>100	1	>100
Number of wafers per run	10...50	1	4
Level of automation	Low, increasing	Fully	Fully
Level of fab integration	Low, increasing	High	High
Yield managing strategies	Evolving	Excellent	Excellent
Metrology	in-situ + ex-situ	ex-situ + virtual	ex-situ + virtual + in-situ?

New devices such as 3D-NAND can change the industry ...

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Summary

LAYTEC Knowledge is key

Summary

- Optical in-situ metrology has become standard in compound epitaxy
- Control loops on different levels a with different time constants are used
- In-situ metrology provides equipment, process and product data for APC, SPC and equipment health monitoring
- In Si-industry, new complex devices that require muti-layer-growth in one chamber provide opportunities to integrate optical in-situ metrology
- LayTec‘s 3DStaR allows in-situ monitoring of PECVD growth of SiO_2/Si_xN_y multilayer stacks
- Thickness can be measured with accuracies as good as <1nm
- In-situ monitoring reveals previously unknown growth effects
- Apertures as small as 1mm can be used
- In-situ metrology can complement ex-situ and virtual metrology and provide substantial additional benefits for complex layer structures

LayTec Knowledge is key

Knowledge is key

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