Industrial-scale metrology for automated in-line and in-situ quality control

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LayTec AG

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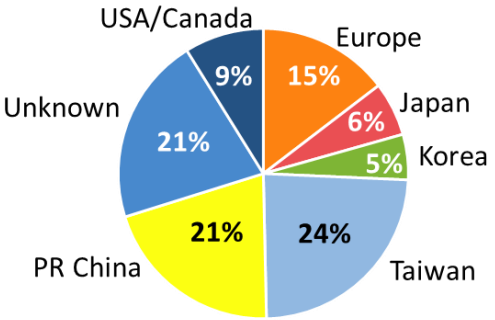
Knowledge is key

Outline

- Company overview
- The quality challenge
- Sampling mode vs. feedback time
- Methodology for thin film quality control
- Examples for thin film quality control
- Economic metrics
- Future trends
- Conclusions

LayTec at a glance…



- 1999 foundation of LayTec
- ~70 employees based in Berlin
- Optical in-situ & in-line metrology solutions for thin film applications
- Strong base of academic and industrial partners for future developments
- World market leader of in-situ metrology for LED and LASER production equipment
- Entering of the in-line market in 2009
- In-line systems installed in PV, glass and display industry
- Worldwide more than 2400 metrology systems installed

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Integrated metrology for various industries and markets

In-line

Conveyor,
Roll-to-Roll, in-chamber

In-situ

ALD, sputtering,
PECVD, MOCVD, …

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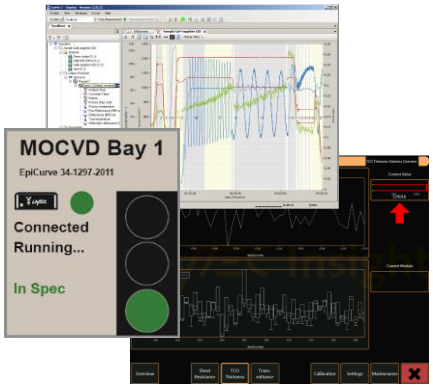
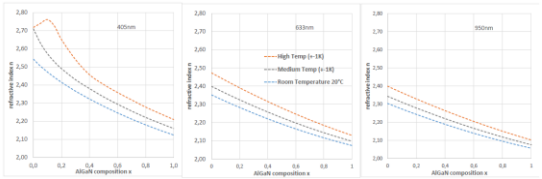
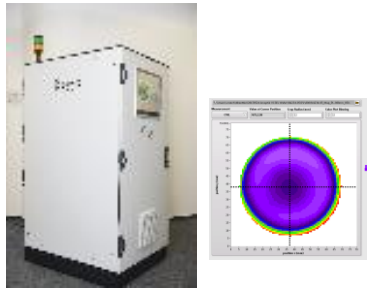


Software & Analysis

Simulation, analysis, fit, integration



Material data base



Mapping

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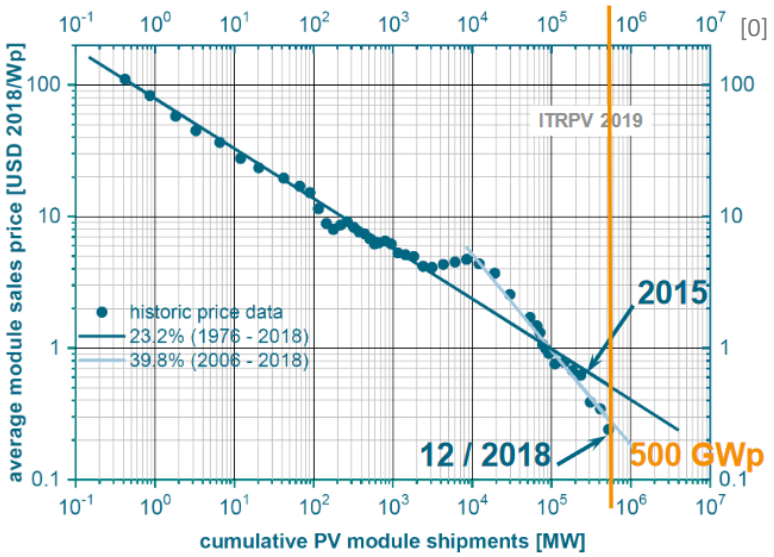
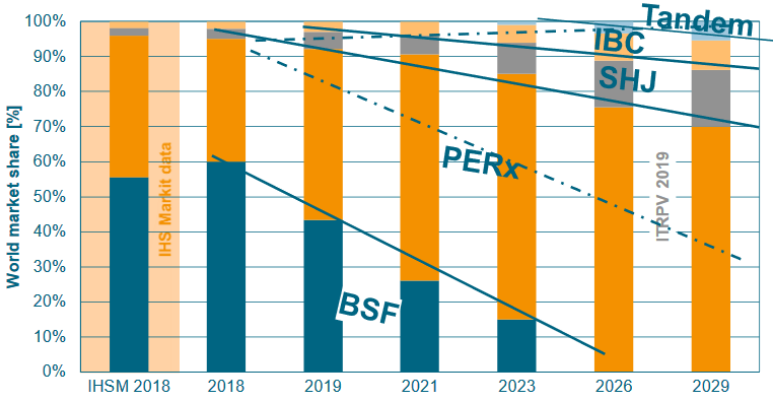
Higher yield @ lower variability? (PV as example)

- Extreme price pressure in PV (similarly LED, semi etc.)
- Complexity of processes / devices increases – so does # of parameters to control
- Device efficiency needs to increase → stricter binning and sorting
- Yield and uptime have to be maximum

→ *Tighter specs for more complex processes*

→ *Less scrapping of out-of-spec modules acceptable*





[0] *Reproduced from ITRPV 2019*

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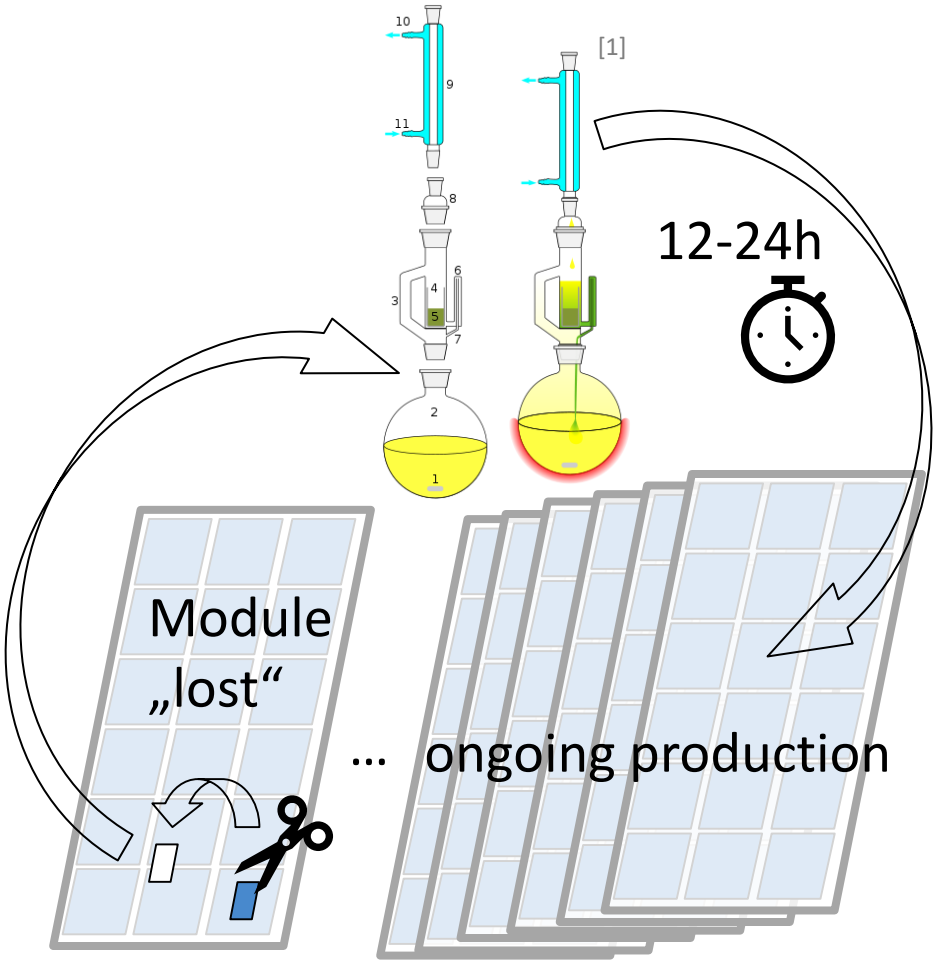
Statistical process control: EVA cross-linking

Destructive



[1] *Original PNG by Quantockgoblin, SVG adaptation by Slashme [Public domain]*

Statistical process control: EVA cross-linking

Destructive

12-24h

Module „lost“

… ongoing production

Non-destructive

Some minutes

No module „lost“

… ongoing production

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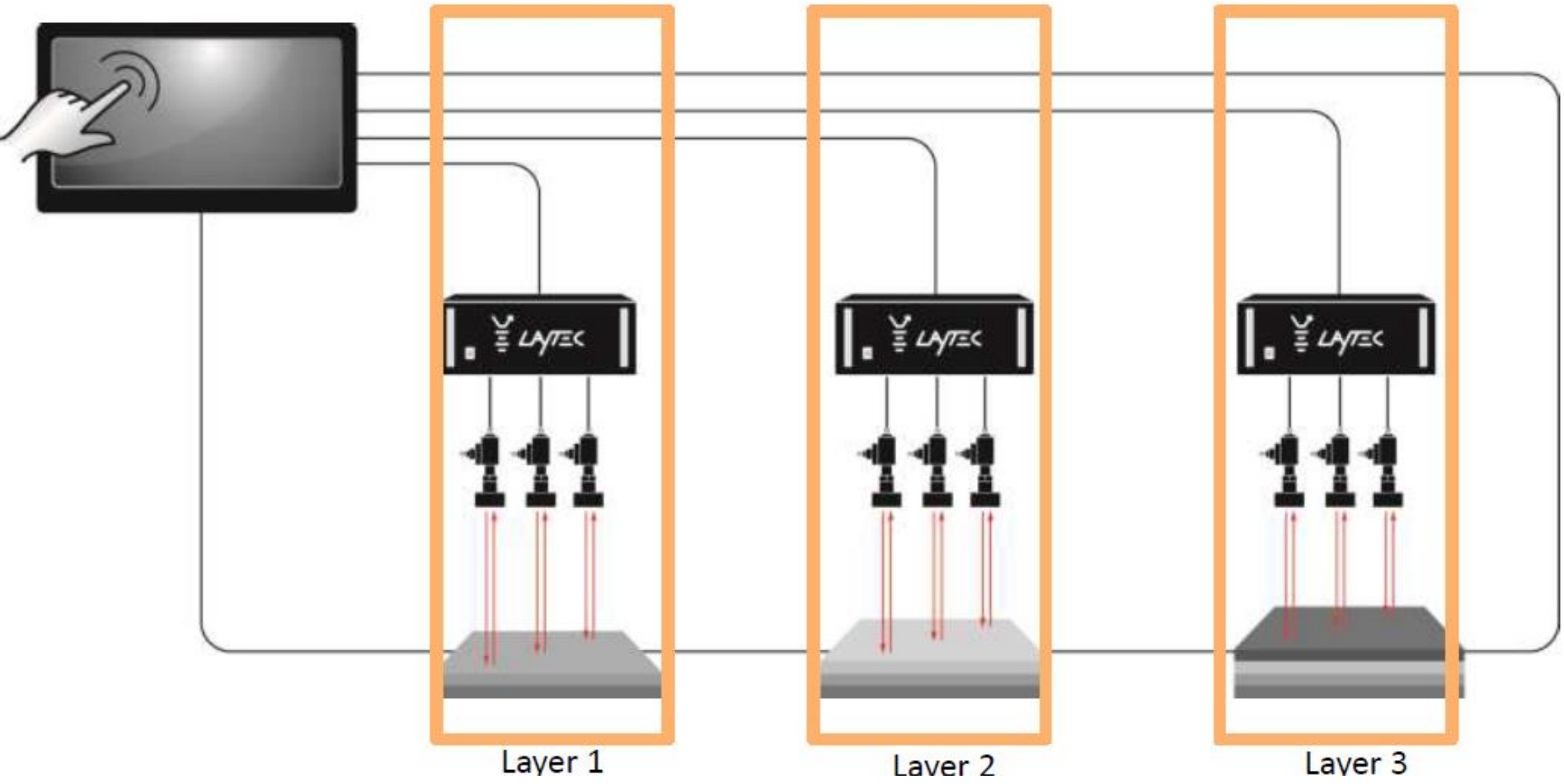
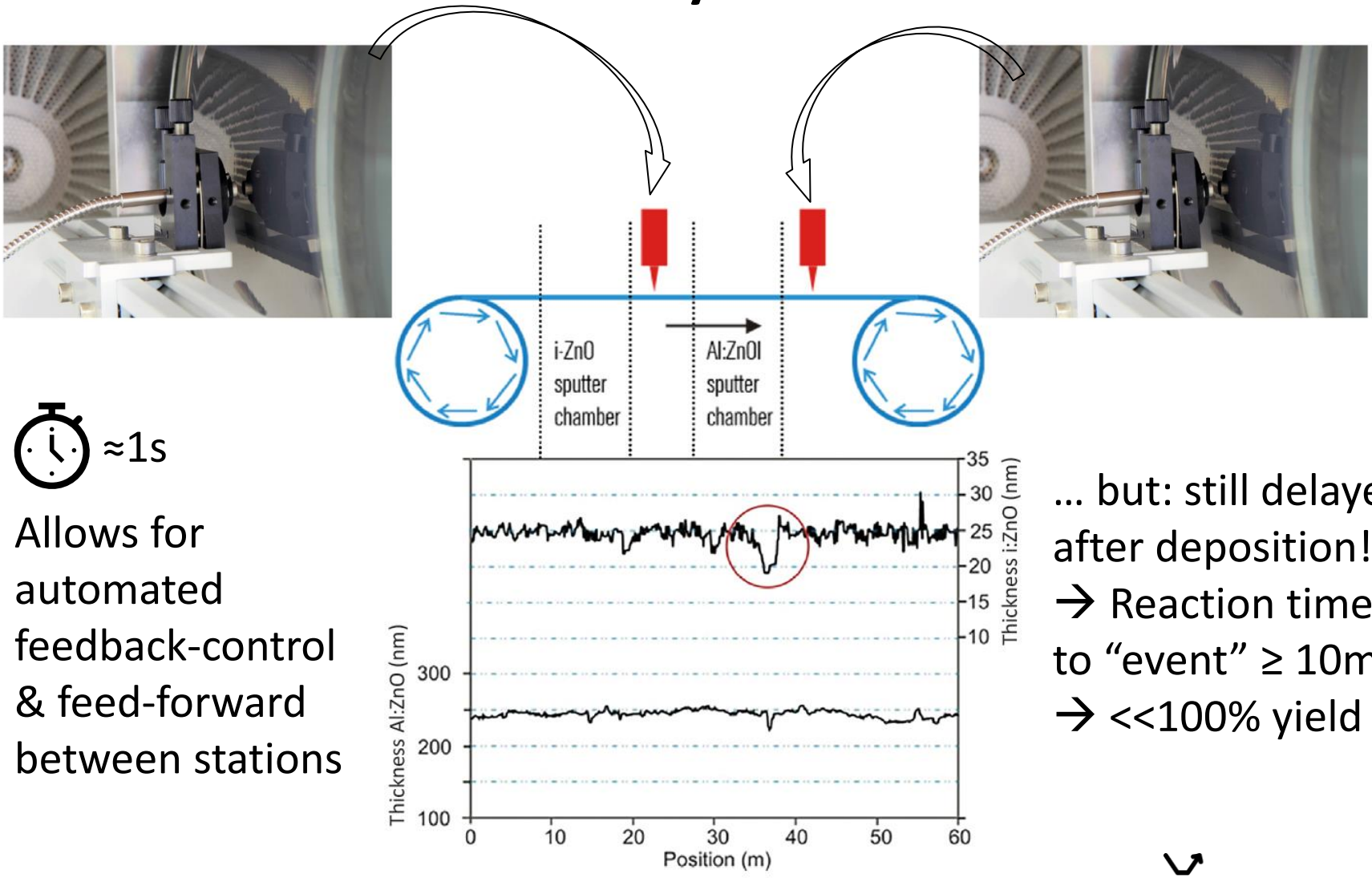
100% in-line control: General system layout



100% in-line control: R2R-layer thickness



≈1s

Allows for automated feedback-control & feed-forward between stations

… but: still delayed after deposition!
→ Reaction time to “event” ≥ 10min
→ <<100% yield

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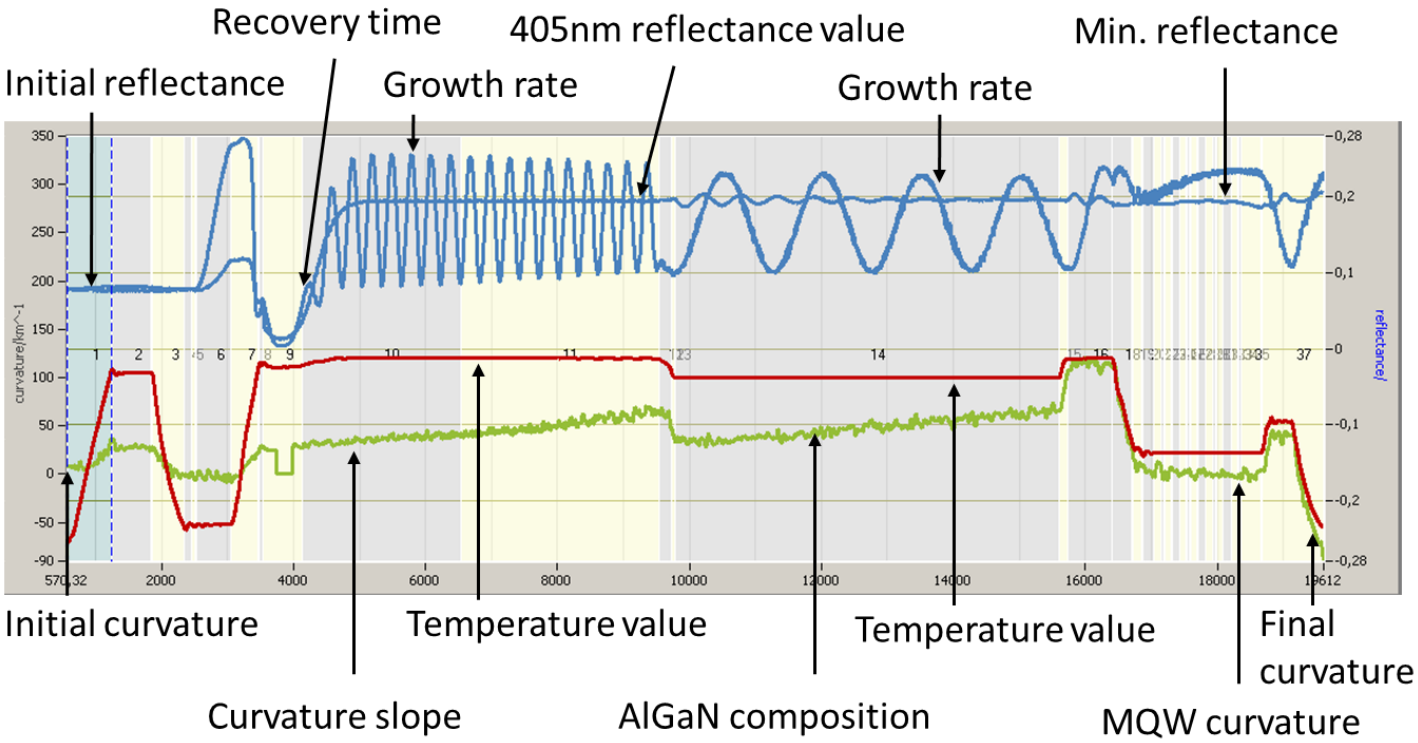
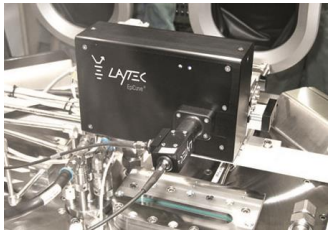
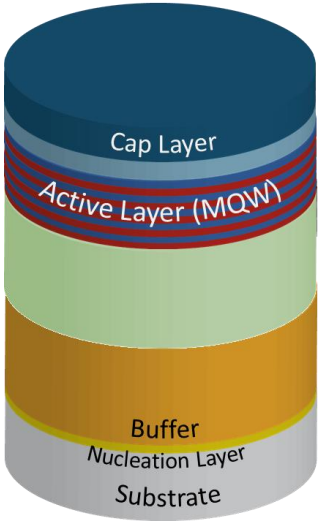
100% in-situ growth control: MOCVD for LED growth





LED cross section



≈1s

Allows for immediate reaction to “save” device by operator or by automated feedback-control

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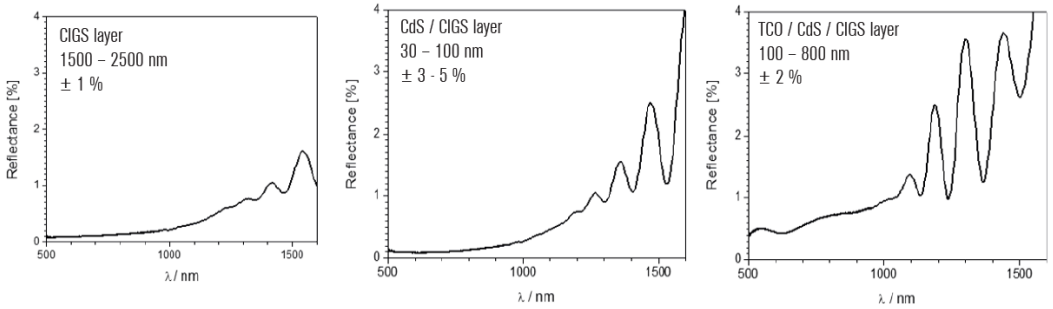
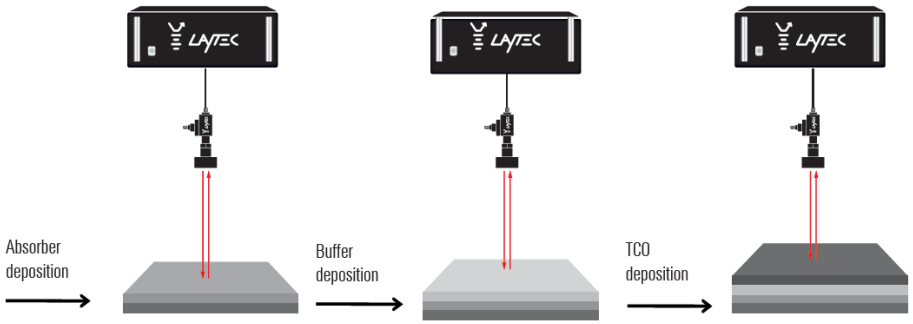
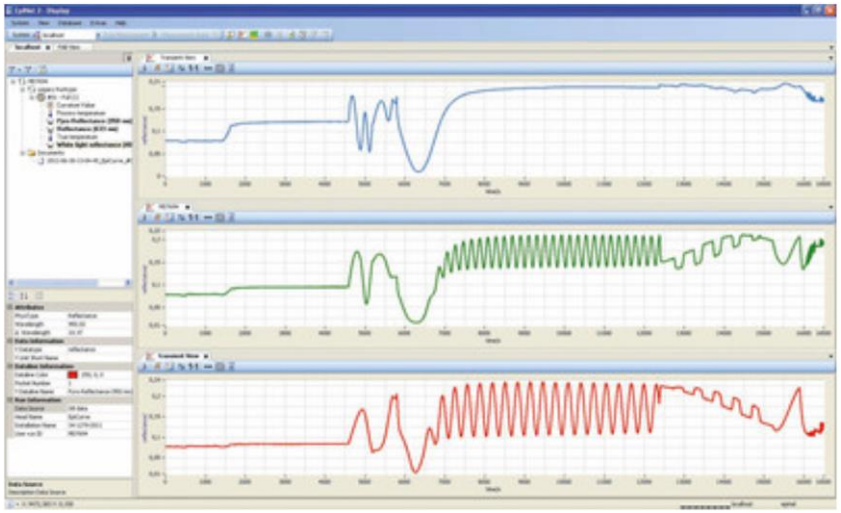
Reflectance measurements





Spectral systems used for static layers → in-line.
For in-situ analysis, single-, multiwavelength or spectral systems can be used → analysis of time-dependent intensity



Detection of reflectance from non-metallic layers. Interference of light reflected at different interfaces yields information about (optical) thickness of layers.

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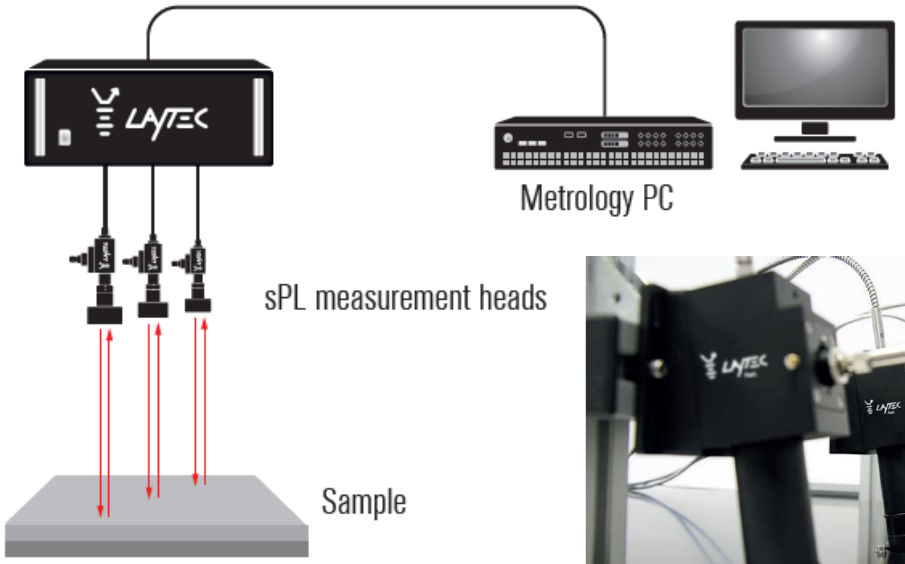
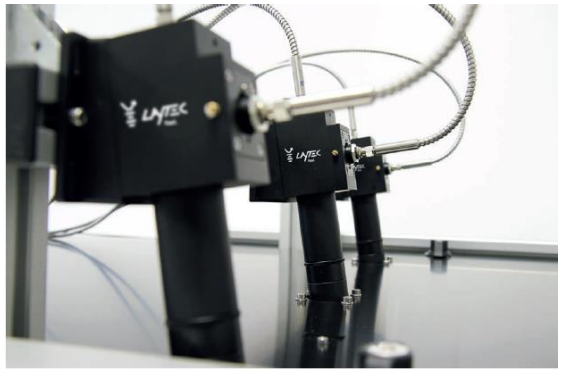
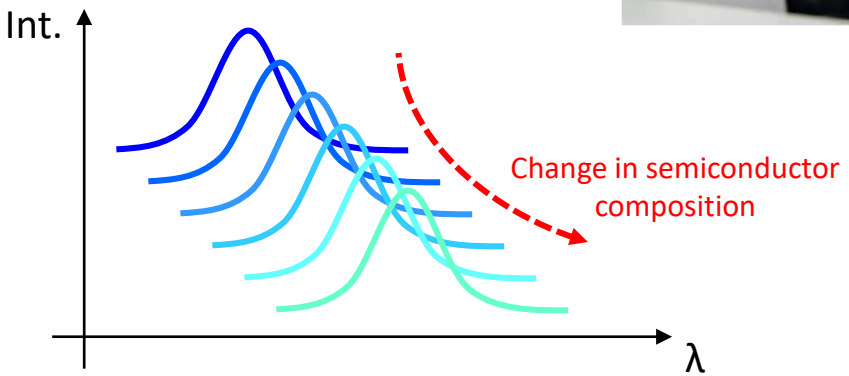
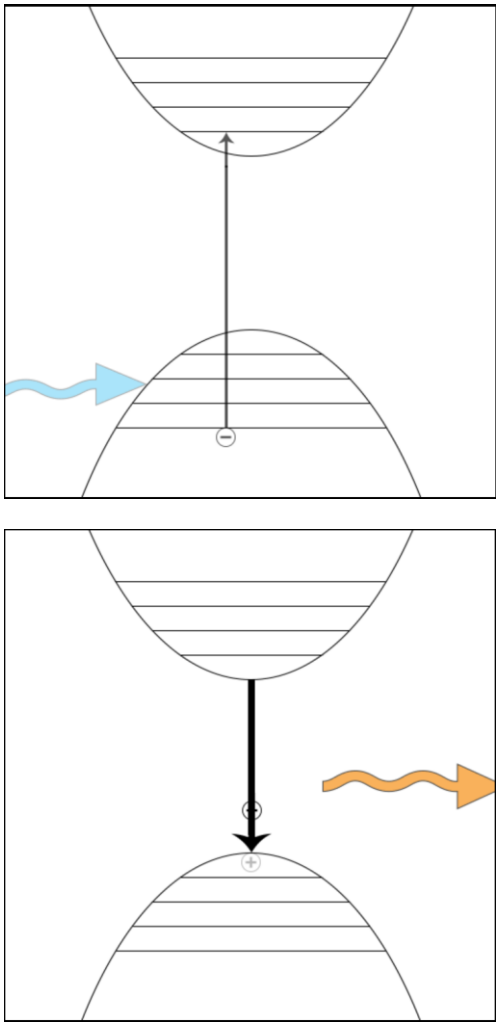
Photoluminescence









[2]

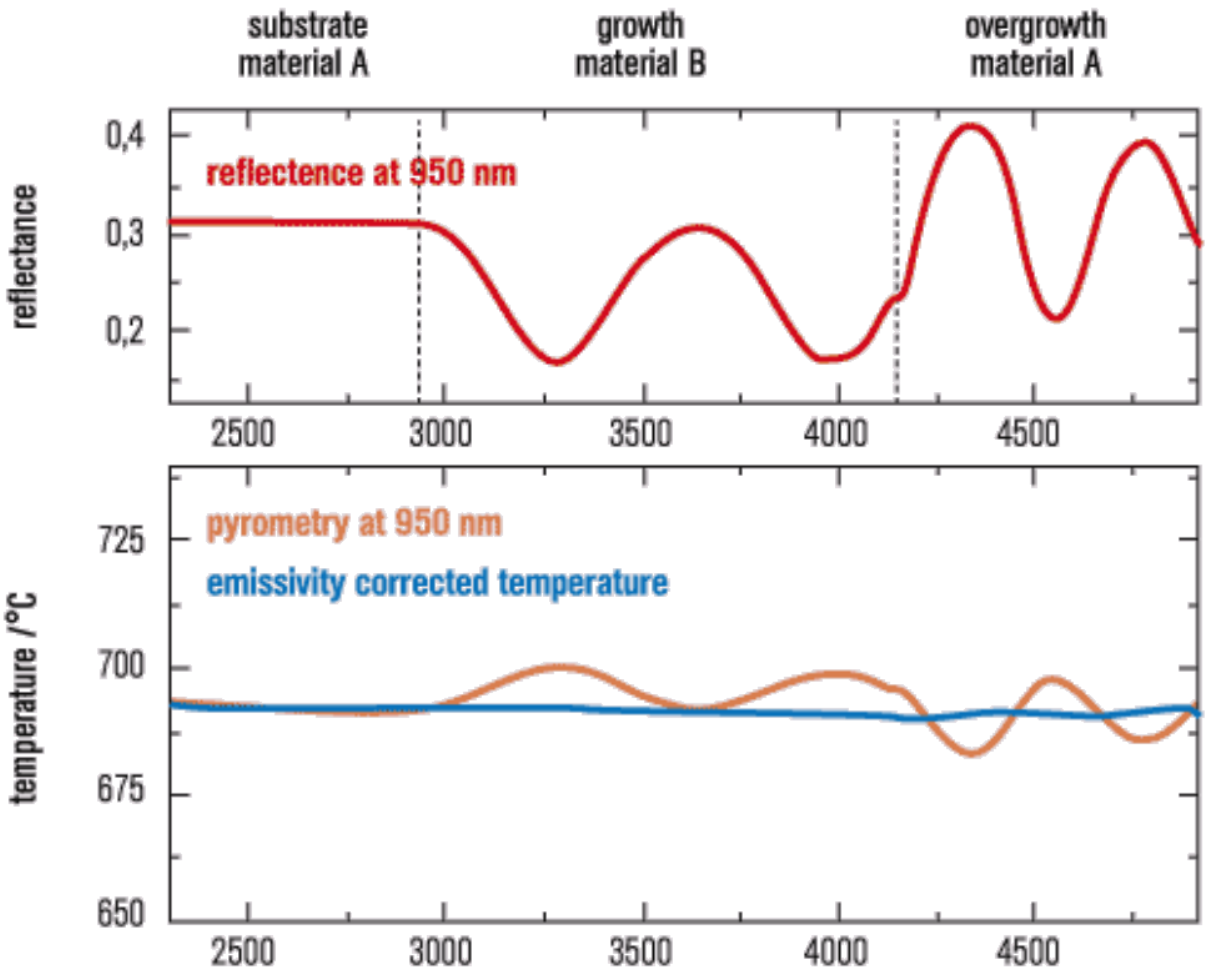
[2] *BlyumJ [CC BY-SA 4.0 (https://creativecommons.org/licenses/by-sa/4.0)], https://upload.wikimedia.org/wikipedia/commons/0/03/Photoluminescence_animation.gif*

Pyrometry

Determining temperature by detecting heat radiation.

By correcting pyrometry signal by reflectance signal of identical wavelength emissivity changes of the surface (due to deposition) can be corrected for.

“True temperature” can be measured. Usually applied for T > 400°C.



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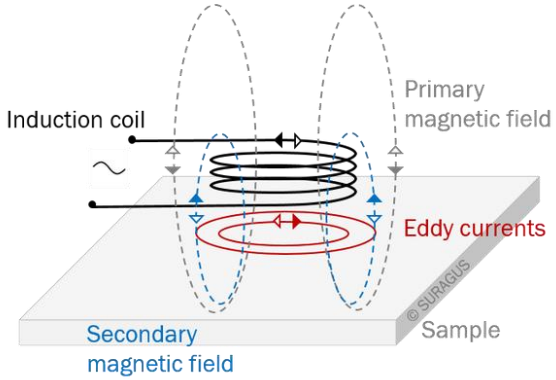
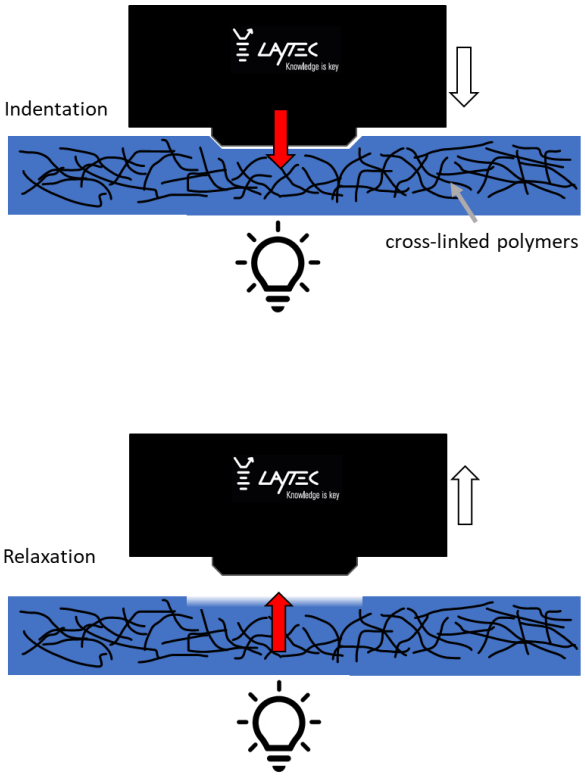
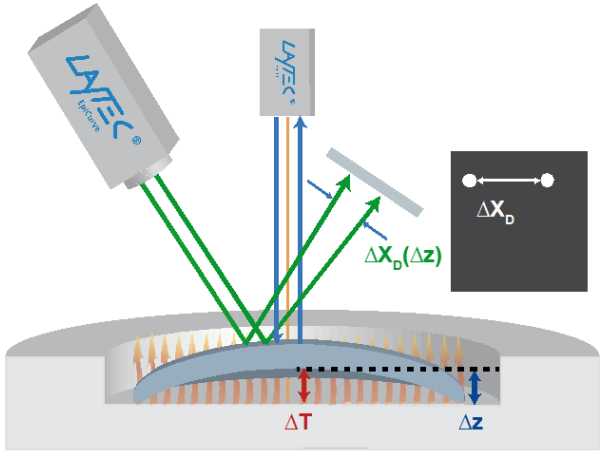
Eddy-Current sensing, EVA Cross-linking, bow, …



Conductivity and thickness of conductive layers. Eddy currents induced in sample surface. Frequency determines penetration depth and sensitivity.

Quality of cross-linking PV encapsulation polymers by thermo-mechanical probing of relaxation upon indentation.





Bowed wafer

Control of wafer bow caused by lattice strain of different semiconductors during epitaxy to prevent crystal defects or cracks. Quantifies deflection of laser spots on wafer surface due to wafer bowing.

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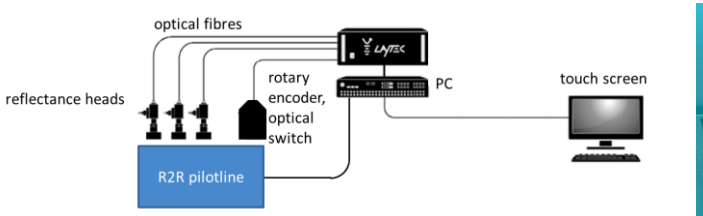
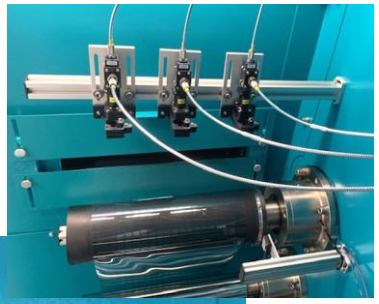
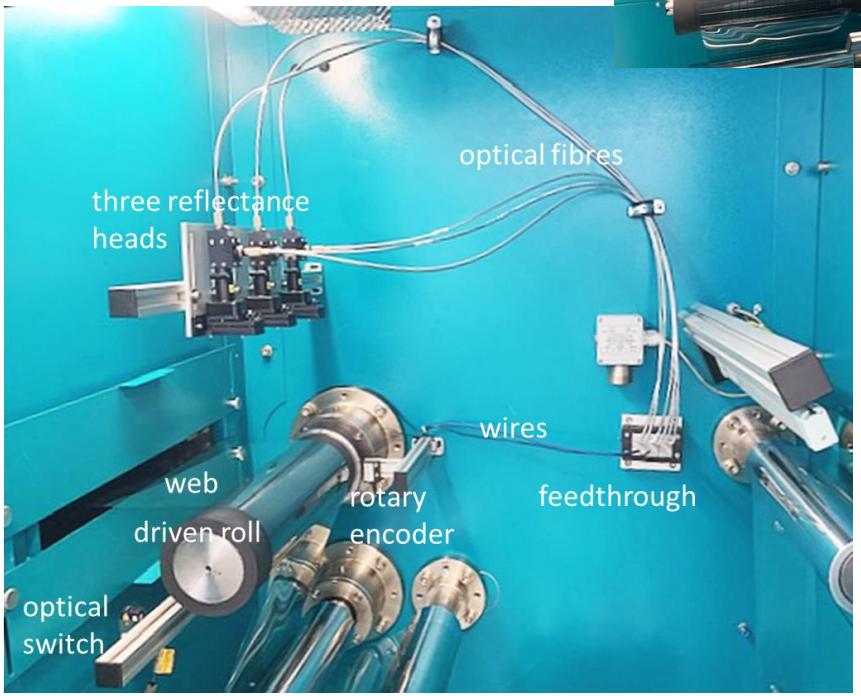
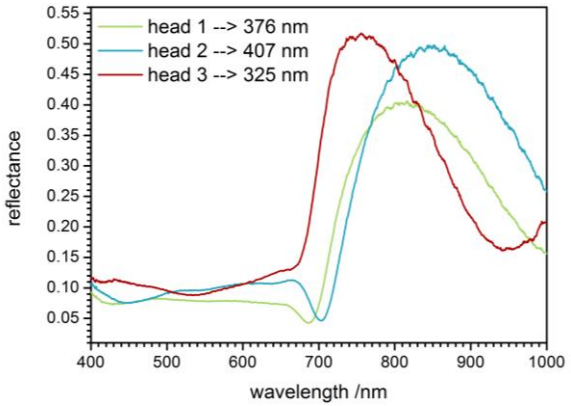
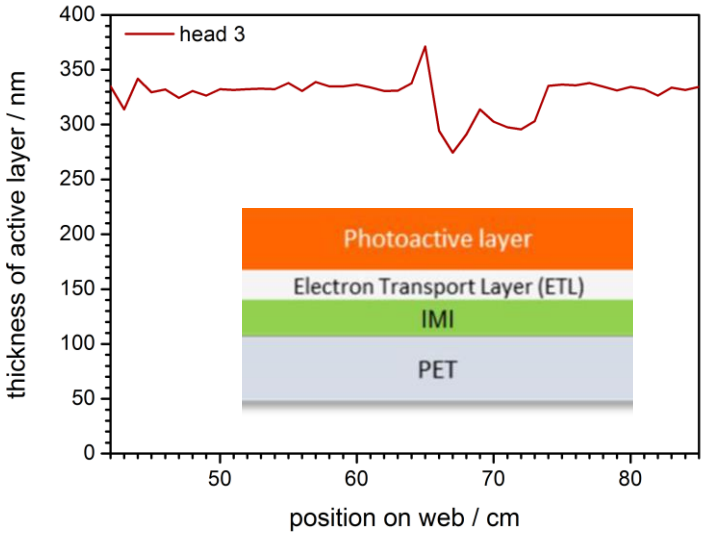
In-line thickness measurement at R2R-OPV-line









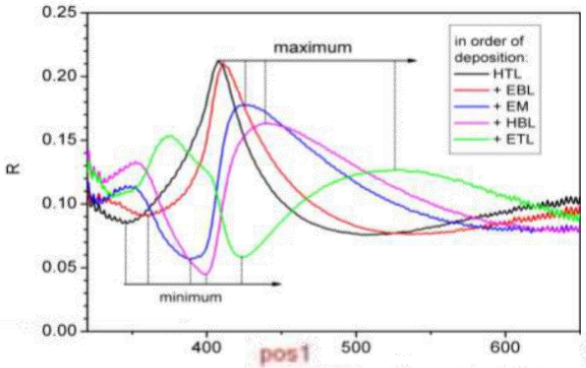


This project has received funding from the European Union's HORIZON 2020 research and innovation programme under Grant Agreement No 768707.

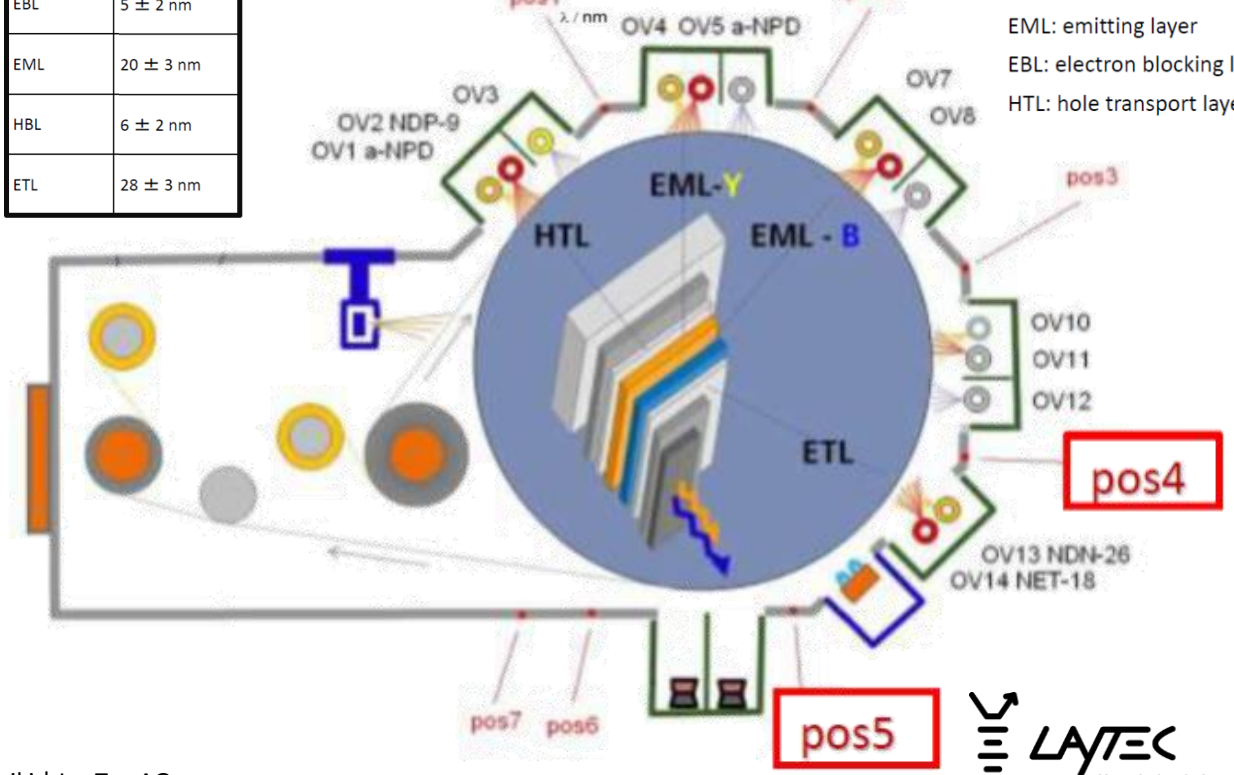
In-chamber in-line control of OLED growth

- “in-chamber”-in-line analysis of OLED-R2R-process
- Thickness measurement between process steps
- Precision of ~3nm demonstrated
- All layers of stack analyzed

Layer	Foil, in-situ
HTL	51 ± 3 nm
EBL	5 ± 2 nm
EML	20 ± 3 nm
HBL	6 ± 2 nm
ETL	28 ± 3 nm



ETL: electron transport layer
HBL: hole blocking layer
EML: emitting layer
EBL: electron blocking layer
HTL: hole transport layer



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Economic value of metrology: Example 1 (simplified)

- **PV Module price: 0.20€/W**p (lowest price May 2019, module price index) [4]
- Thin film PV line capacity: **100 MWp/year**
  - revenue from modules: $100*10^6$ Wp * 0.20€/Wp
  - Assume **100 Wp/ module → 1,000,000 modules per year**
  - Assume **Metrology** leads to improved process control **adding an average x Wp/module** → add x*0.20 €/module
  - **Additional revenue** generated by metrology:
    - **x = 1 Wp: 200,000 €/year**
    - x = 2 Wp: 400,000 €/year
    - x = 3 Wp: 600,000 €/year
    - x = 4 Wp: 800,000 €/year
    - **x = 5 Wp: 1,000,000 €/year**
- Assume **metrology price of 100,000 €**
- Return of Investment (ROI): **ROI** = Net Income/ Cost of Investment:
  - **1 Wp: 200 % after 1 year // 5 Wp: 1000% after 1 year**
- Pay Back Period (**PBP**): **1 Wp: 6 months // 5 Wp: 37 days**

[4] *https://www.pv-magazine.com/module-price-index/*

Economic value of metrology: Example 2 (simplified)

- Implement new **metrology in thin film PV frontend (absorber layer deposition)**
- Apply **tighter spec thanks to new metrology**
- Estimate**: After Absorber** production = **38% of module production cost** [5]
- Estimate: **Between Absorber and Flasher I** (before front glass) = **23% of module cost** [5]
- Assume **production cost = module price** (zero loss/profit): 0.20€/Wp [4]
- Thin film PV line capacity: 100 MWp/year
  - **"Until-absorber"-costs** from modules: 38%*100*10^6 Wp * 0.20€/Wp = **7.6 M€/year**
  - **"After-absorber-frontend"-costs** from modules: 23%*100*10^6 Wp * 0.20€/Wp = **4.6 M€/year**
  - Assume **95% production yield in frontend and 100% in backend**
  - Assume **5% frontend yield occurs exclusively @ absorber deposition**
    - loss = 380 k€/year if modules are scrapped after absorber deposition
    - Loss = **380 k€/year** **+ 230 k€/**year are scrapped after Flasher I
- Assume **metrology price of 100,000 €**
- Return of Investment (ROI): **ROI** = Avoided loss / Cost of Investment:
  - **230%** after one year
- Pay Back Period (**PBP**): **78 days**

[5] *K. A. W. Horowitz et al., NREL/PR-6A20-64507, 2015*

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What‘s next

- Cost pressure will require even higher yields
  - Switch from…
    - Destructive –> non-destructive testing
    - Sampling → 100% in-line
    - In-line → in-situ (e.g. control of reaction gas instead of deposition)
- Implement automated feedback-control
- Implement automated feed-forward for…
  - Corrective measures in subsequent process steps
  - Adaptive processes based on previous results
  - Improved analysis based on previous results
- Use of AI for…
  - Identifications of correlations between processes and parameters
  - Identification of process excursions and initiation of counter-measures

Conclusions & outlook

- Price and quality pressure makes metrology a must for industrial production
- Destructive → non-destructive, samling → 100% in-line → in-situ, deposition → chamber atmosphere
- Feedback-time is drastically reduced
- Optical methods well-suited for thin film control, other methods such as eddy current complement
- ROI and PBT for integrated metrology usually very attractive
- Future trends will go towards fully automated control and us of AI for reducing reaction time and identification of correlations

Thank you for your attention!

Thanks also go to…

- LayTec co-workers and external partners for their contributions
- Partners of Smartline EU project for cooperation and sharing of results: ltfn, oet, Suragus, …
- EU for funding of Smartline

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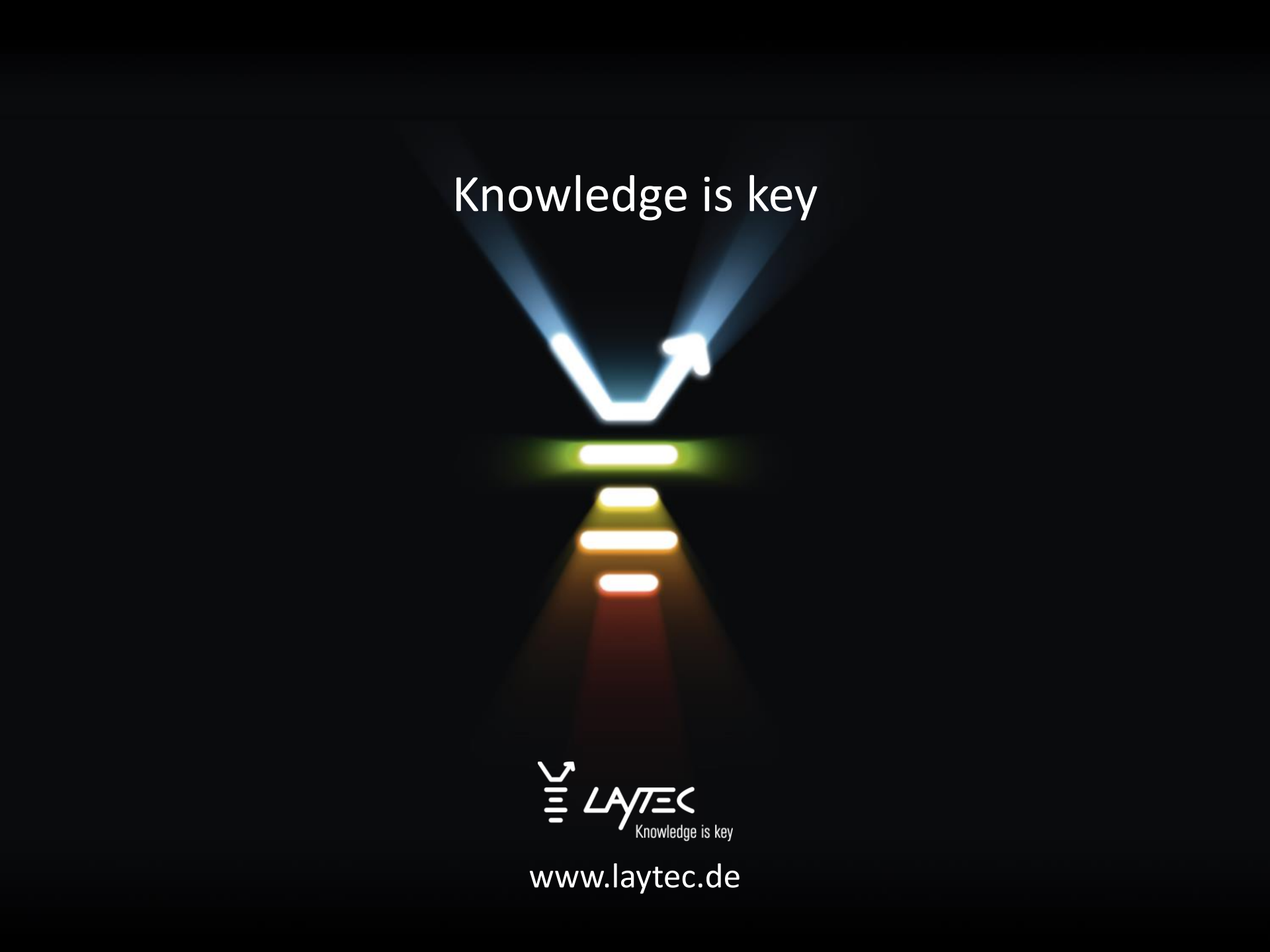

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