第七届钙钛矿与叠层技术论坛
7th Perovskite & Tandem Cell Technology Forum
2025.4.16-17
Changzhou China

Recent advances in *in-situ* and *in-line* monitoring of perovskite thin film formation

Dr. Christian Camus

LayTec AG

Berlin, Germany

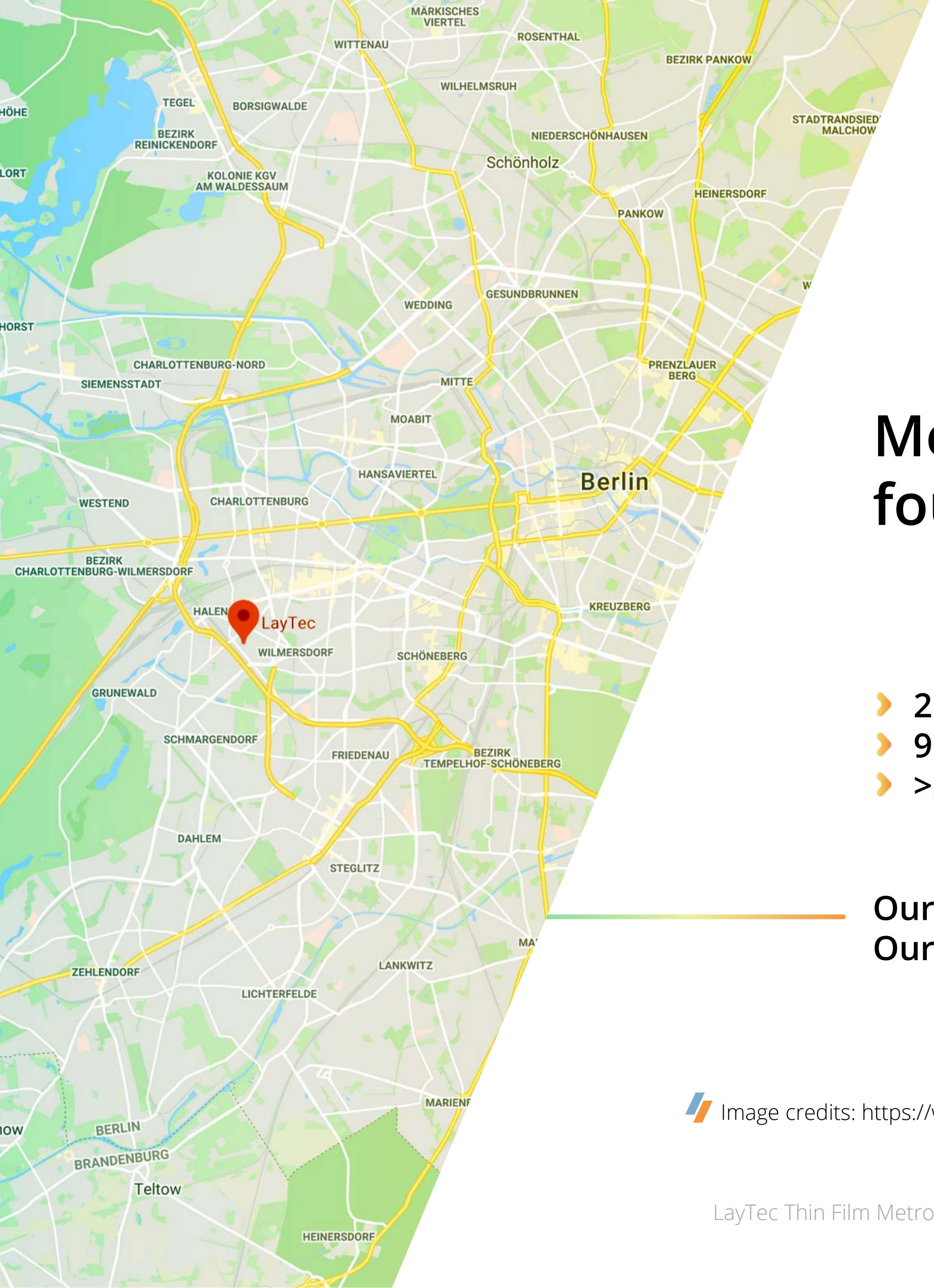
达珂机电

MEMBER OF THE NYNOMIC GROUP

Outline

- Company introduction
- Metrology methods & monitoring parameters
- In-situ monitoring of perovskite formation
- In-line monitoring of perovskite formation
- Metrology capabilities for entire perovskite stack
- Summary & outlook

Outline



NYNOMIC
THE PHOTONICS GROUP

Metrology company founded 1999 in Berlin

- 25 years old
- 90 employees
- >3500 systems sold
- spun-off out of TU Berlin
- Operating worldwide
- Member of Nynomic group

Our business: Process-integrated optical metrology
Our markets: Semiconductor and thin-film industry & academia incl. lighting, laser, PV, glass coating …

Image credits: https://www.google.de/maps

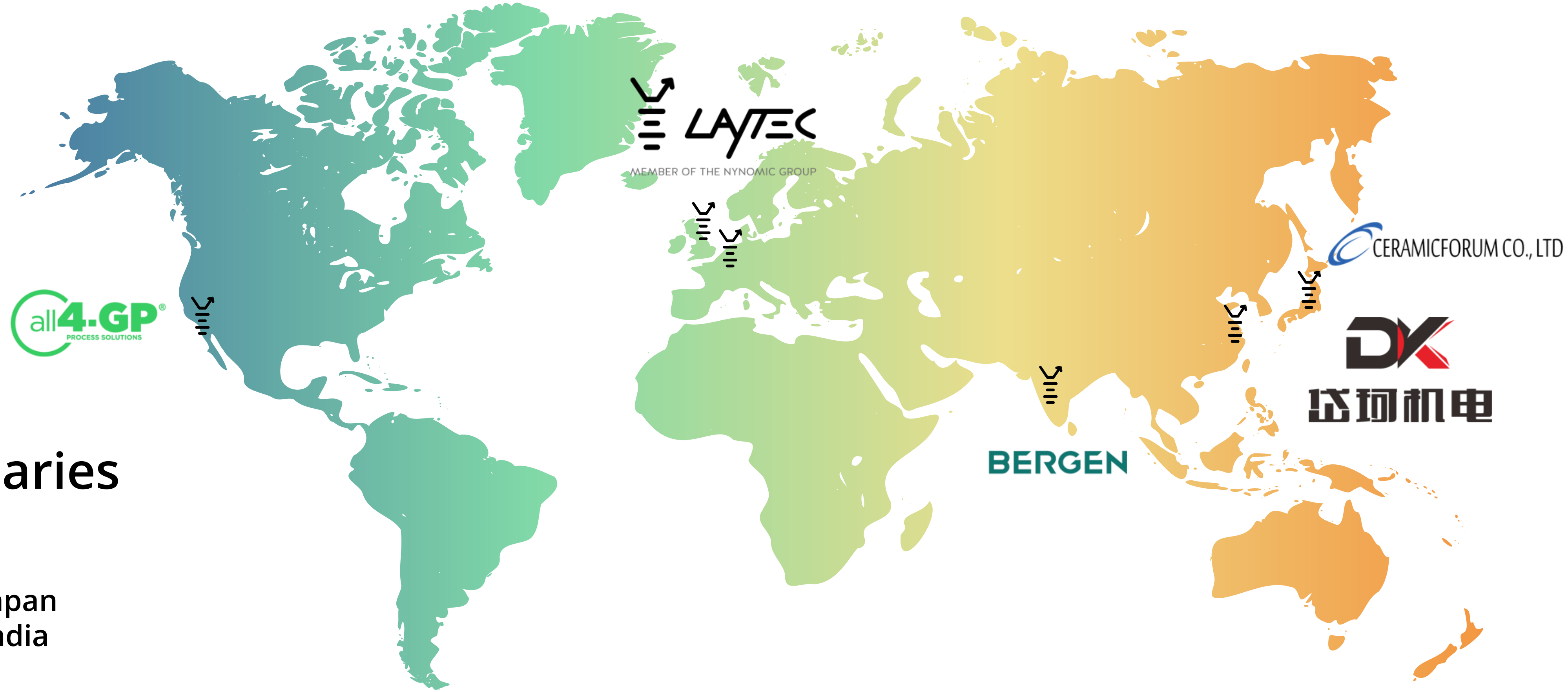
Worldwide network of sales and service partners

Headquarter

- Berlin, Germany

Sales & service offices, subsidiaries (solar applications)

- North America
- Europe
- China
- Japan
- India



PV company & institute references

HZB Helmholtz Zentrum Berlin
HySPRINT Helmholtz Innovation Lab
Caelux
REC
ZSW
AZUR SPACE Solar Power GmbH
Q CELLS
ASTRONERGY
Fraunhofer CSP
Fraunhofer ISE
Flisom Flexible Solar Modules www.flisom.ch
JABIL
CNBM CTF SOLAR
risen

LAYTEC MEMBER OF THE NYNOMIC GROUP

PRESS RELEASE: March 2025

Caelux selects LayTec to ensure unprecedented quality of perovskite-based solar glass

This partnership will further Caelux's mission to make solar energy more powerful and cost-effective

Berlin, Germany — March 5, 2025 — LayTec proudly announces that Caelux®, a California-based pioneer in
utilizing perovskites to make solar energy more powerful and cost-effe
advanced optical inspection tool for quality assurance in its state-of-th
metrology tool will help Caelux to obtain maximum yield and thin film
based solar modules, meant to serve as a performance-boosting front gl

Caelux provides the simplest path for silicon photovoltaic module com
technology to boost their product's performance. Caelux creates a pero
that can be used as a power-producing front sheet for nearly all traditic
today. As perovskites convert UV and visible light more efficiently than
light through to the silicon layer, the resulting perovskite/silicon tand
energy than silicon alone, for the same panel area.

Through this partnership, LayTec's fully automated optical metrology
measurements of film thickness, reflectivity, transmittance, and sheet
control and enabling adaptation of the measurement mode. LayTec's sys
of quality and homogeneity across all key layers of the thin film stack, allo
precise quality assurance and obtain further insights into the correlati
performance.

"This partnership with LayTec is a critical step in our commitment to provi
glass," said Scott Graybeal, CEO of Caelux. "The invaluable insights an
inspection tools will allow us to implement a level of precision that is
innovation. We're looking forward to utilizing LayTec as we bring Caelu
how perovskites can be leveraged to boost solar in an impactful, cost-eff

"We are honored to support Caelux on its path towards mass productio
glass," said Volker Blank, CEO of LayTec. "Providing customized metrology
technologies from the pilot to the high-volume manufacturing scale has b
very much looking forward towards the next steps of this trustful partne

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LAYTEC MEMBER OF THE NYNOMIC GROUP

PRESS RELEASE: March 2025

Caelux One is an innovative product that integrates seamlessly into existing photovoltaic module manufacturing processes to boost performance, reduce installation costs, and accelerate the proliferation of lower cost solar panels.

Caelux's perovskite technology is compatible with new silicon photovoltaic modules at all deployment sites. The architecture requires very few changes to the panel manufacturing process, and no changes to the outdoor panel installation process. The panel manufacturer simply connects silicon and Caelux's perovskite active glass in parallel, in what is known as a "voltage-matched four-terminal architecture".

About LayTec:

LayTec develops and manufactures, among others, integrated in-situ and in-line metrology for thin film PV deposition processes covering a wide range of deposition and film formation techniques for academic as well as mass production environments. Within its metrology portfolio, LayTec provides metrology systems for non-destructive monitoring of film properties such as thickness, color, band gap, sheet resistance, composition and roughness. Currently, the company has more than 3500 metrology systems installed worldwide, serving various fields of the semiconductor and photovoltaic industry, and offers a global customer support and service network www.laytec.de.

About Caelux:

Caelux®'s proprietary technologies improve the performance of any new crystalline silicon module, making solar energy more powerful and cost-effective. Headquartered in Baldwin Park, California, Caelux is at the forefront of the emerging science of perovskites, a special class of nanomaterials. Its flagship product, Caelux® One, is an innovative product that integrates seamlessly into existing PV module manufacturing processes, boosting performance, reducing installed costs, and accelerating the proliferation of solar. For more information, visit www.caelux.com or connect on LinkedIn.

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Email: info@laytec.de | T: +49 (0)30 89 00 55 0

To learn more about Caelux, please contact:
Kristen Aikey, JMG Public Relations
Email: kristen@jmgpr.com

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Caelux

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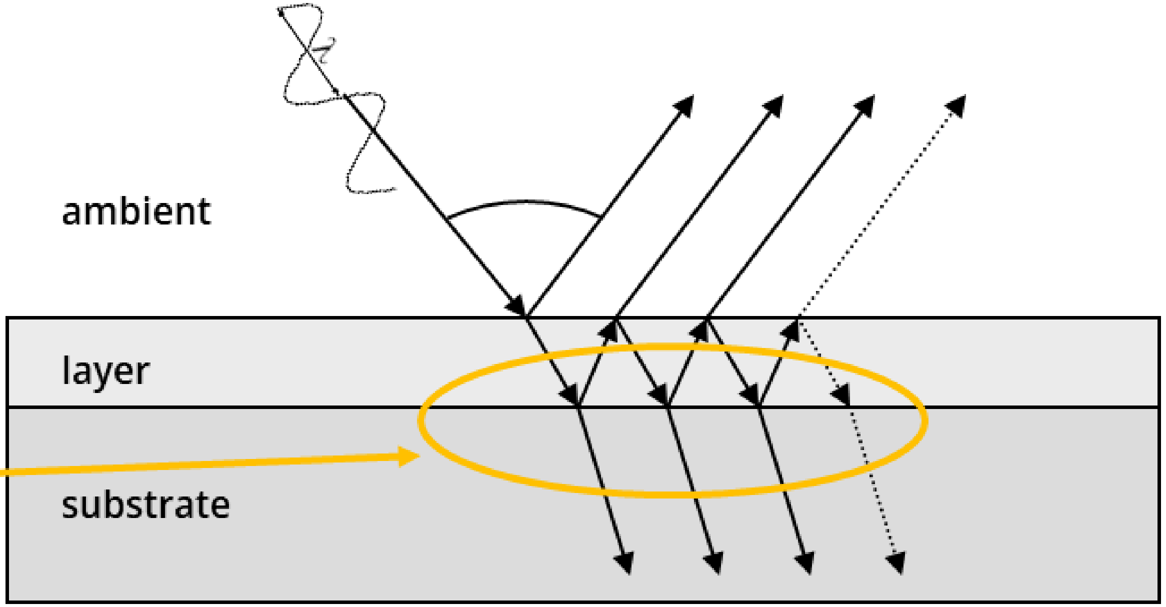
Reflectometry – Thickness measurement

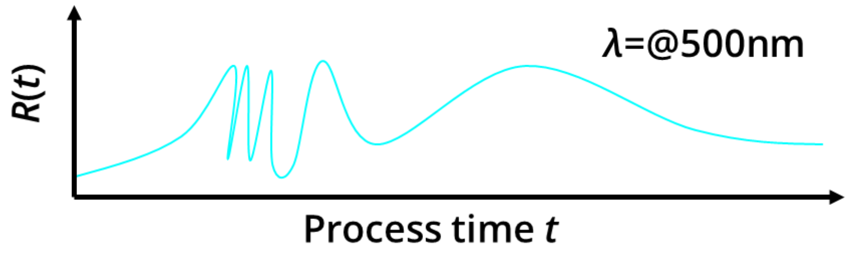
- **Interference of light reflected**
  - at the gas/layer interface
  - at the buried interface
- **Interference is**
  - constructive at 2·n·d = m · l
  - destructive at 2·n·d = (m+1/2) · l



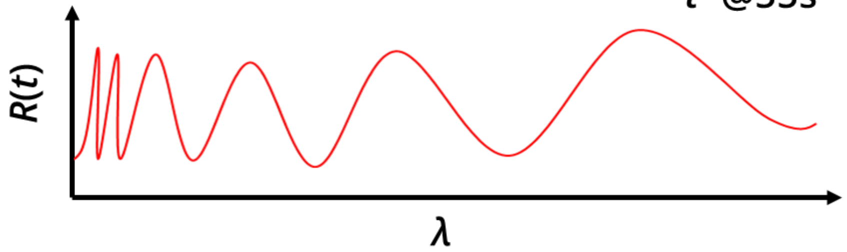
- **Oscillations in reflectance spectra (Fabry-Perot)**
  - → thickness measurement
  - at specific wavelengths (in-situ)
  - white light reflectance (in-situ or in-line)

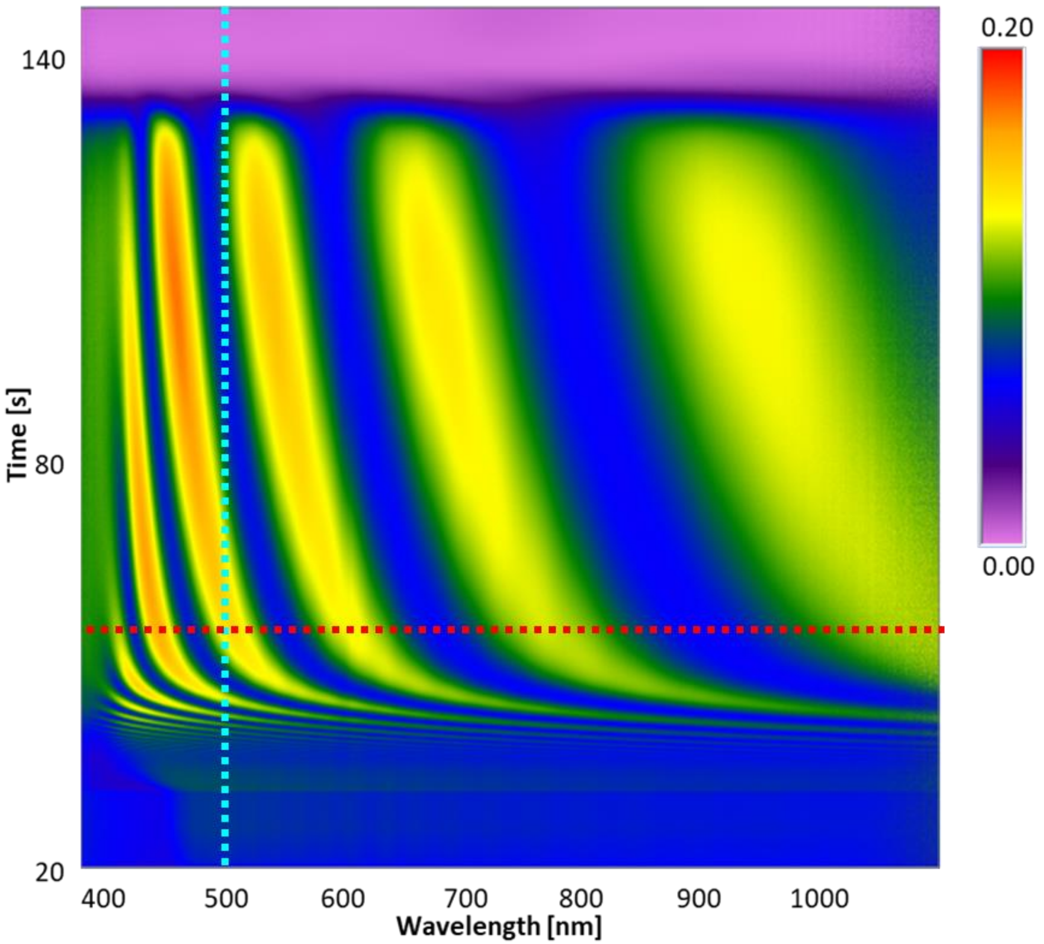
Reflectometry – Thickness measurement

- 1 spectrum per measurement
  - 3D data set: *λ*, *R*, *t* (“spectrogram”)
  - Different ways to analyze:
    - Over time → *R*(*t*, *λ*=const.) → transient analysis

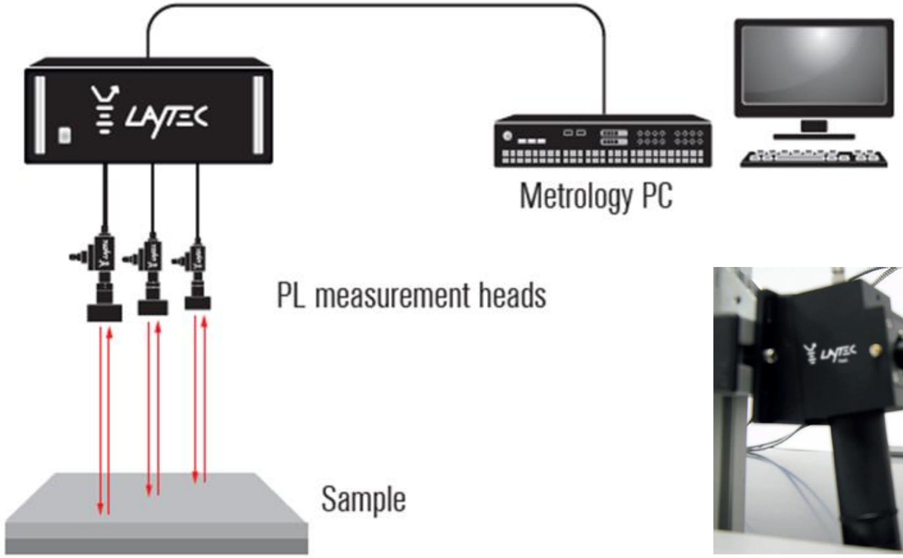


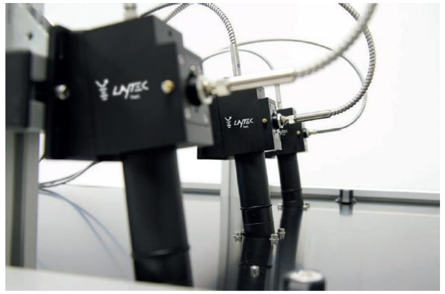
    - Over wavelength → R(t=const., λ) → spectrum analysis





Photoluminescence





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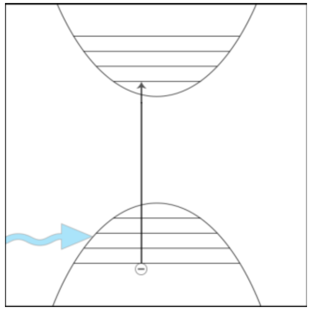
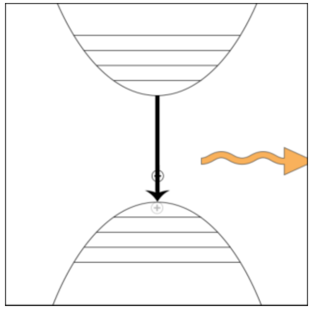
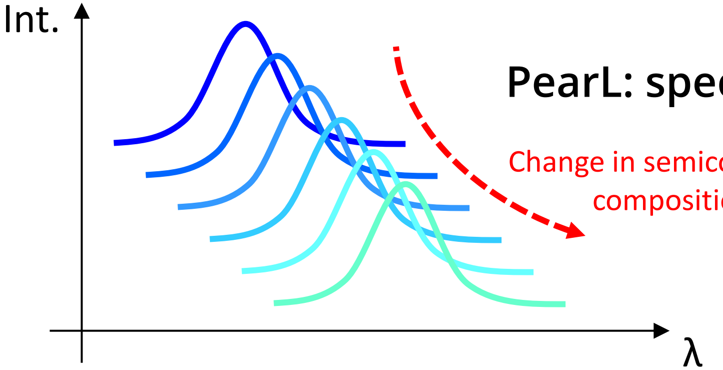


Excitation: photon in

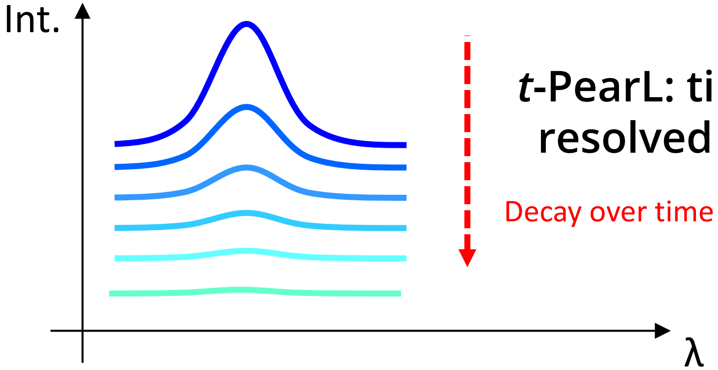
Emission: photon out





PearL: spectral PL

Change in semiconductor composition



***t*-PearL: time-resolved PL**

Decay over time

references: see last slide

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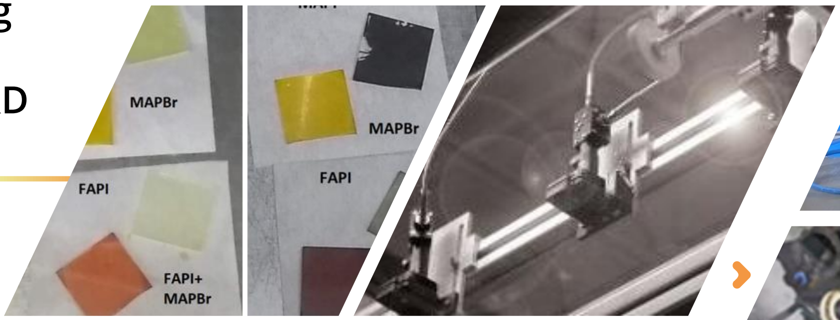
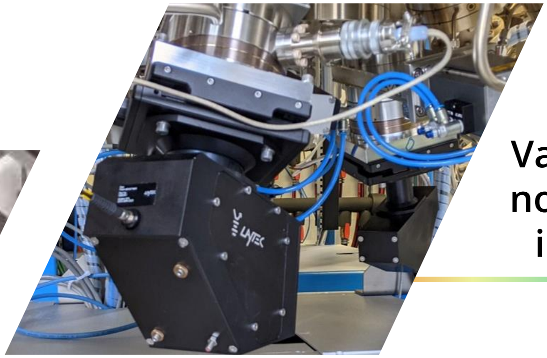
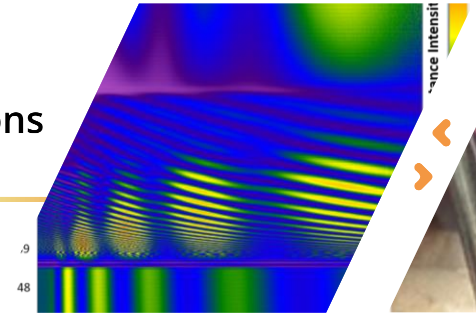
Metrology for high-efficiency photovoltaics

In-situ monitoring of thin film deposition for R&D and production





Vacuum and non-vacuum integration



Visualization of reaction kinetics and phase transitions during thin film formation

Tandem and thin film photovoltaic modules

Measurement of

- layer thickness
- absorption edge
- phase transitions
- reaction kinetics
- color
- composition
- spectral PL
- time-resolved PL
- layer homogeneity
- sheet resistance

Image credits: see last slide

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In-situ monitoring of perovskite formation

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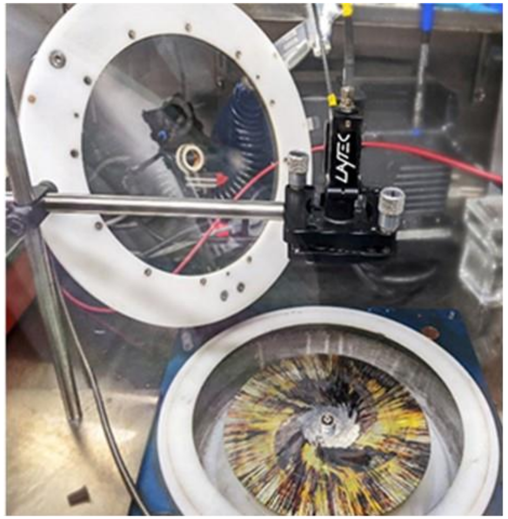
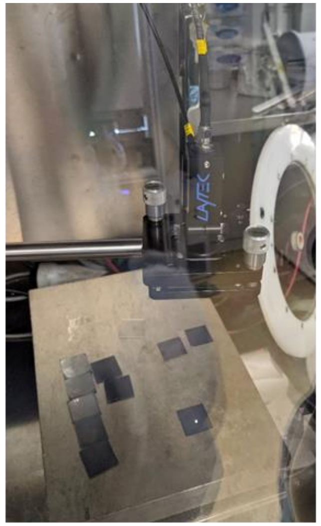
Spin-Coating

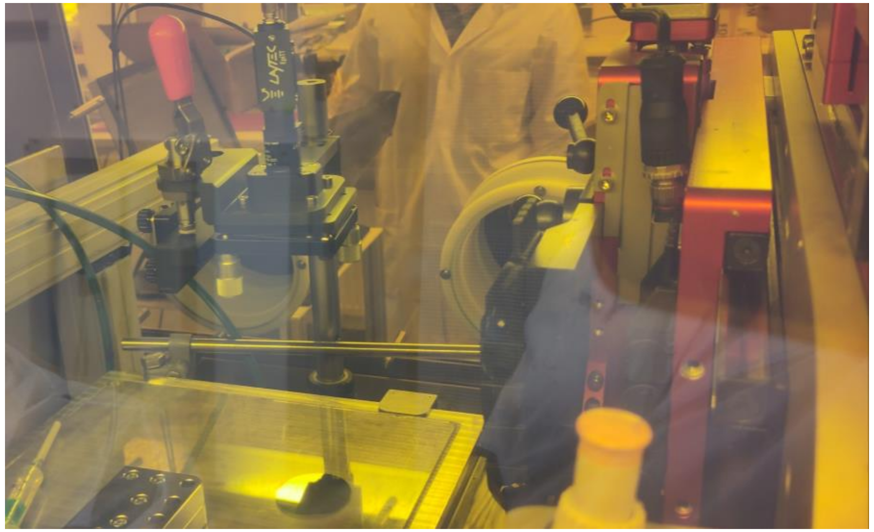


Annealing

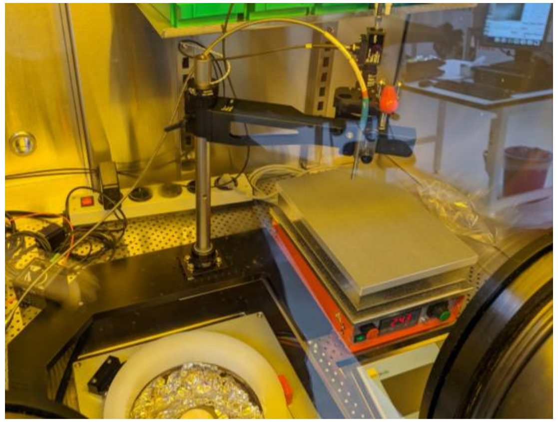


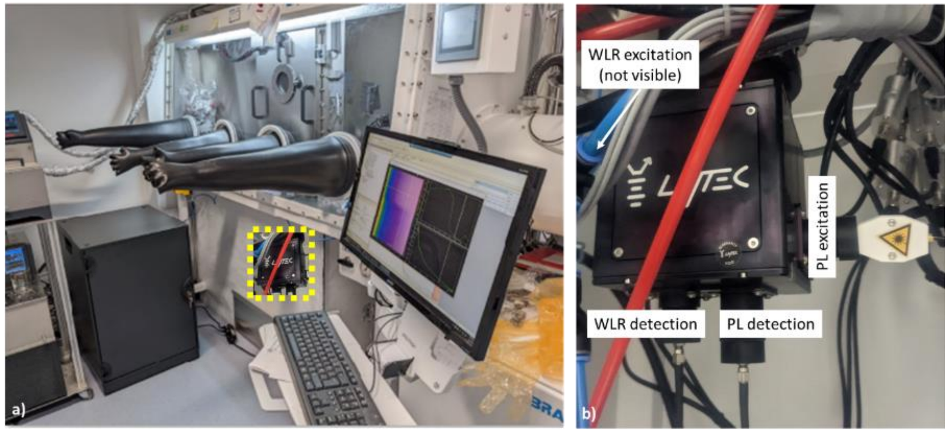
Thermal evaporation

Slot-die coating



Combined spin-coating & annealing set-up





Combined reflectance & PL set-up for PVD

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In-situ monitoring of perovskite formation

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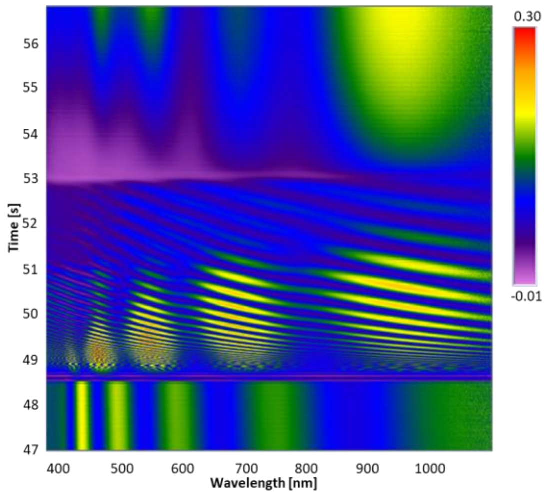
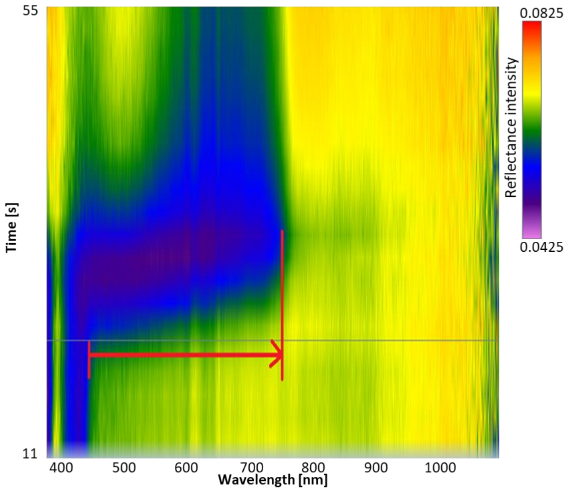
Spin-Coating



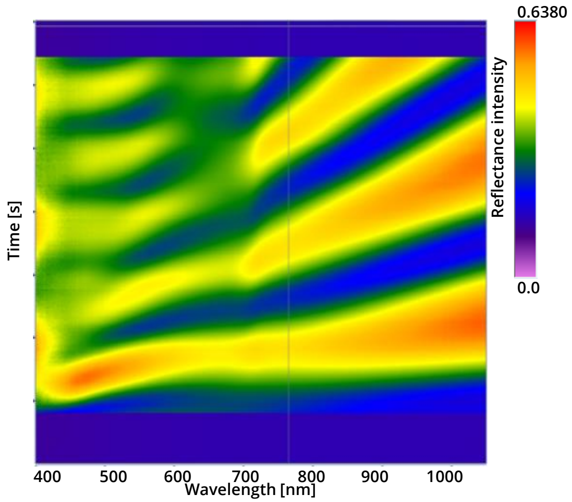
- Early fringes → wet film thickness
- Late fringes → solid film thickness
- Fingerprint of reaction kinetics
- Late fringes → roughness
- Band gap formation

Annealing



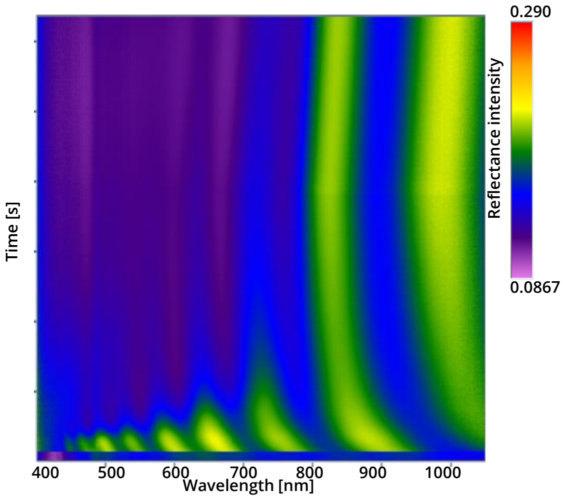
- Band gap formation
- Film degradation by phase transitions

Thermal evaporation



- Fringes → growth rate → thickness
- Band gap formation
- Roughness
- For const. growth rate → n,k
- For known n,k → thickness

Slot-die coating



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In-situ monitoring of perovskite formation

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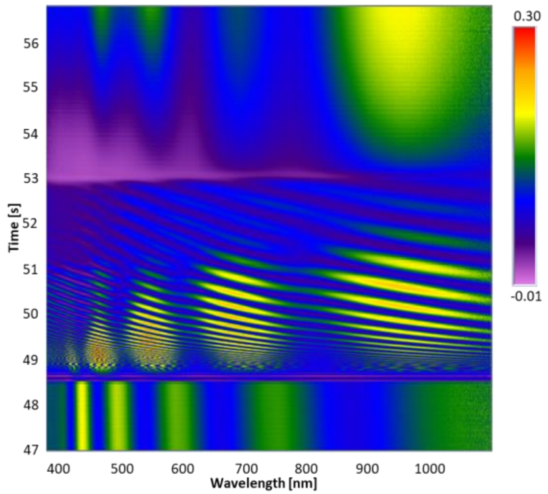
Spin-Coating



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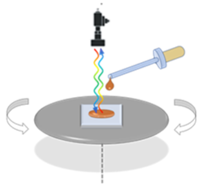
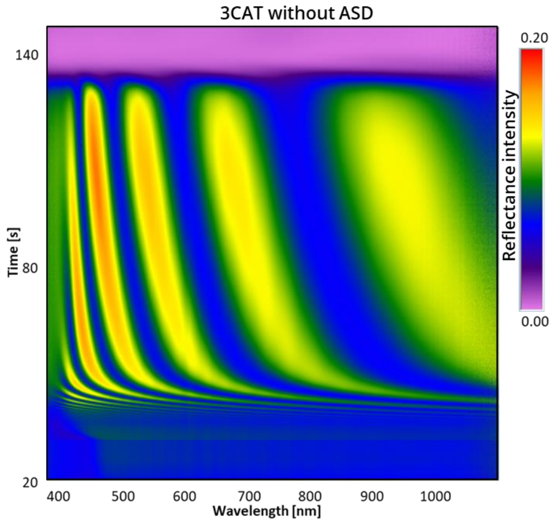
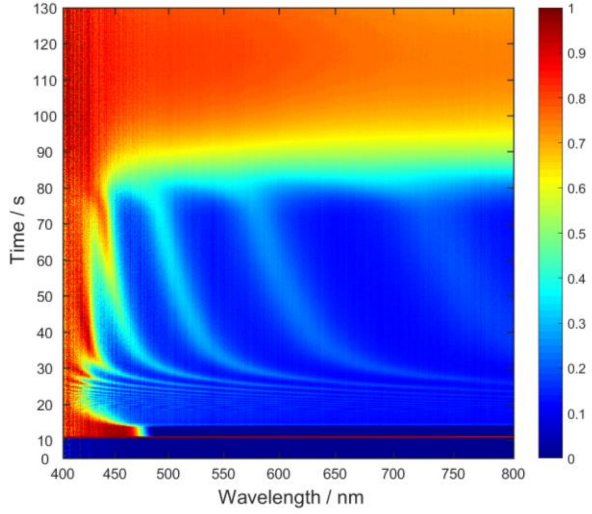
Anti-Solvent Drip: Spin-Coating for 3CAT

3CAT without ASD



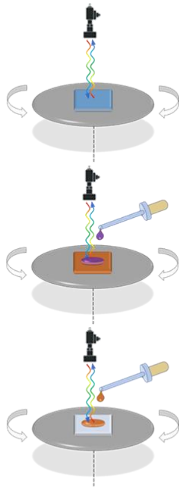


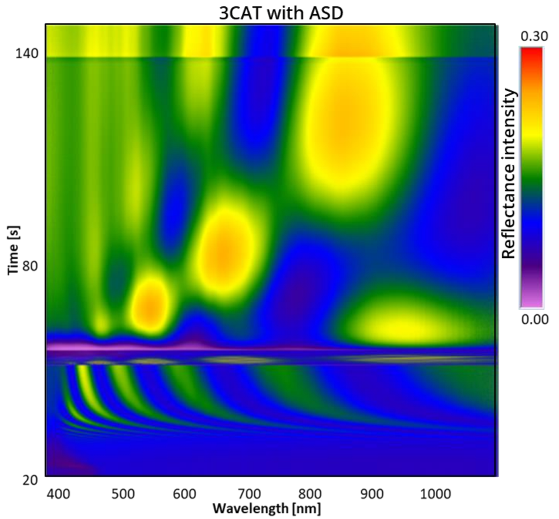
With LAYTEC



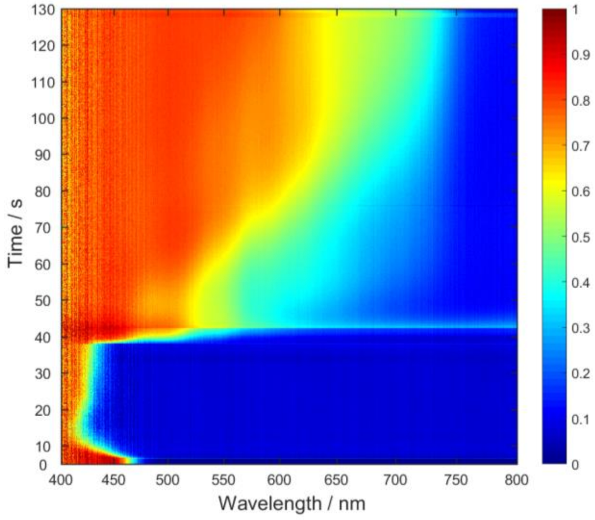
Self-built setup

3CAT with ASD





With LAYTEC



Self-built setup

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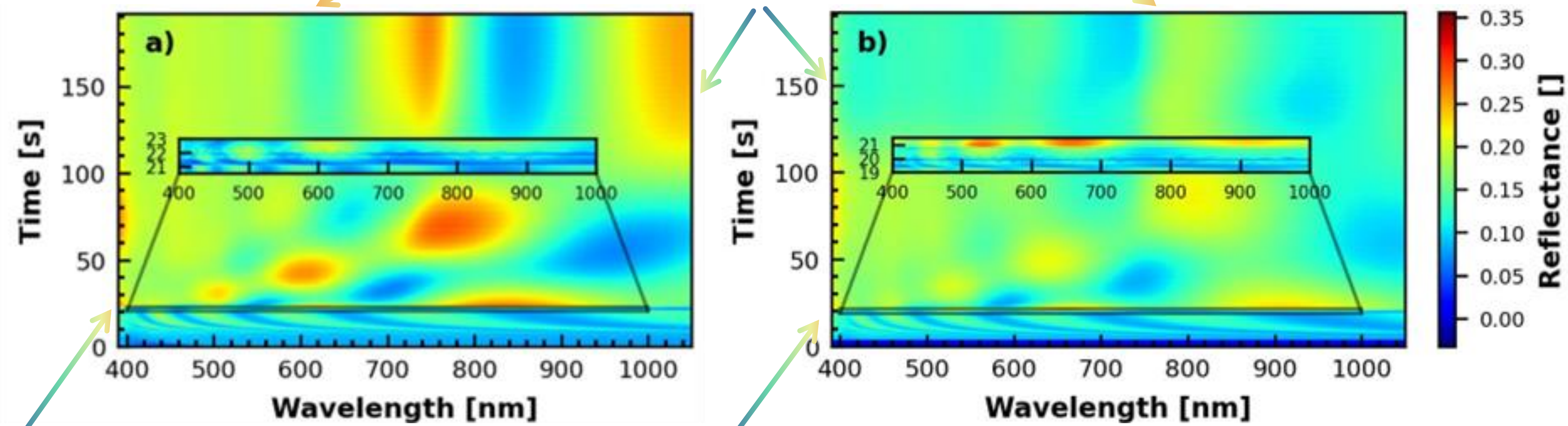
Impact of ASD on 3CAT process

Interference fringes persist → smooth surface due to ASD

Change in pattern (= film properties)



ASD @ t = 21s

ASD @ t = 19s

In-situ monitoring of perovskite formation

Spin-Coating

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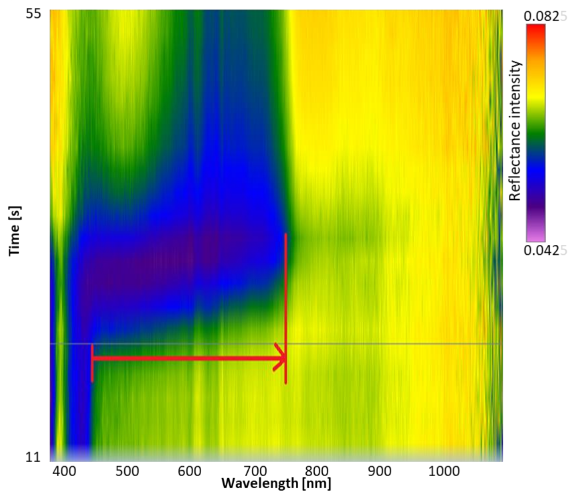
- Band gap formation

Annealing



- Band gap formation
- Film degradation by phase transitions

Thermal evaporation

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Slot-die coating

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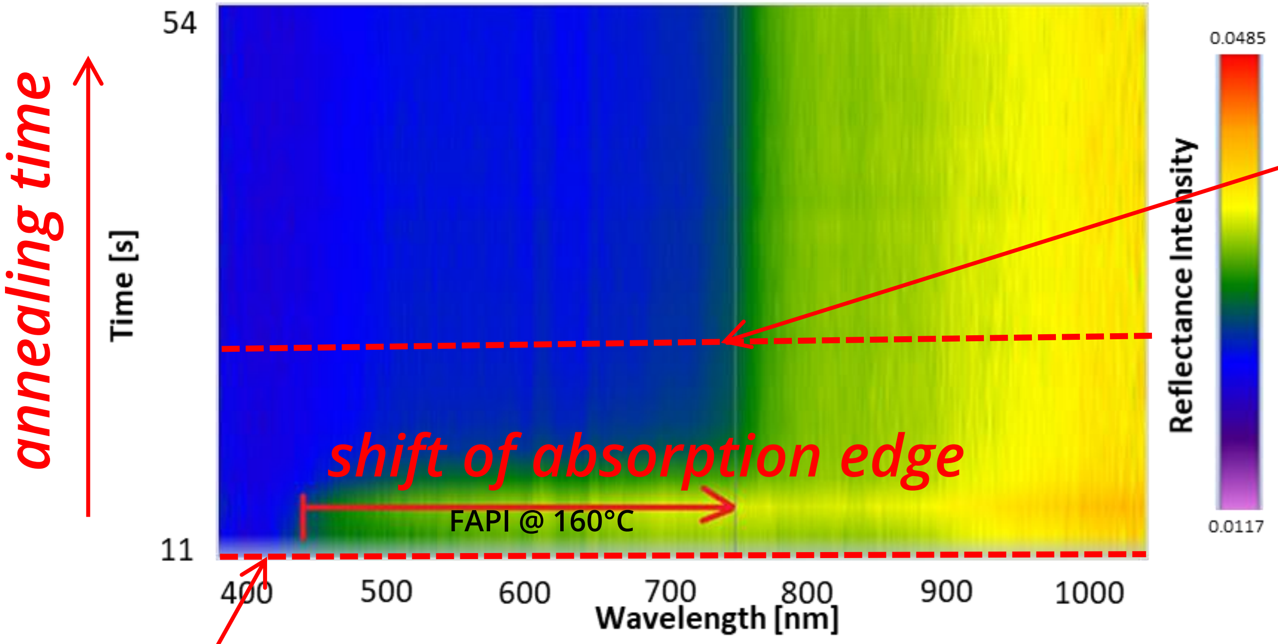
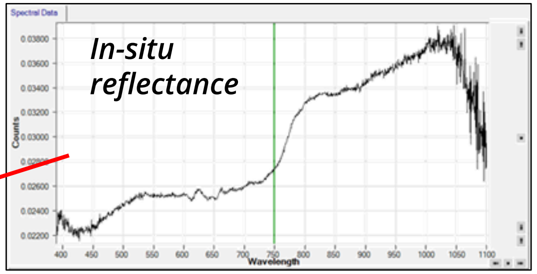
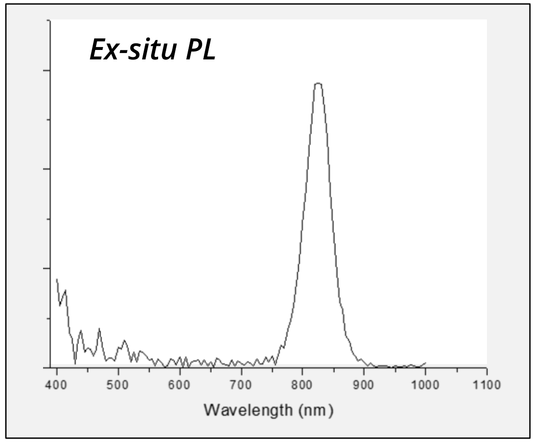
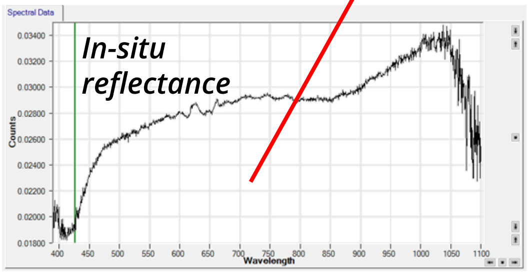
Annealing: As it is supposed to be…









Band gap shifts from ~450nm to 725 during annealing.
Optical absorption edge corresponds to PL emission of final film.

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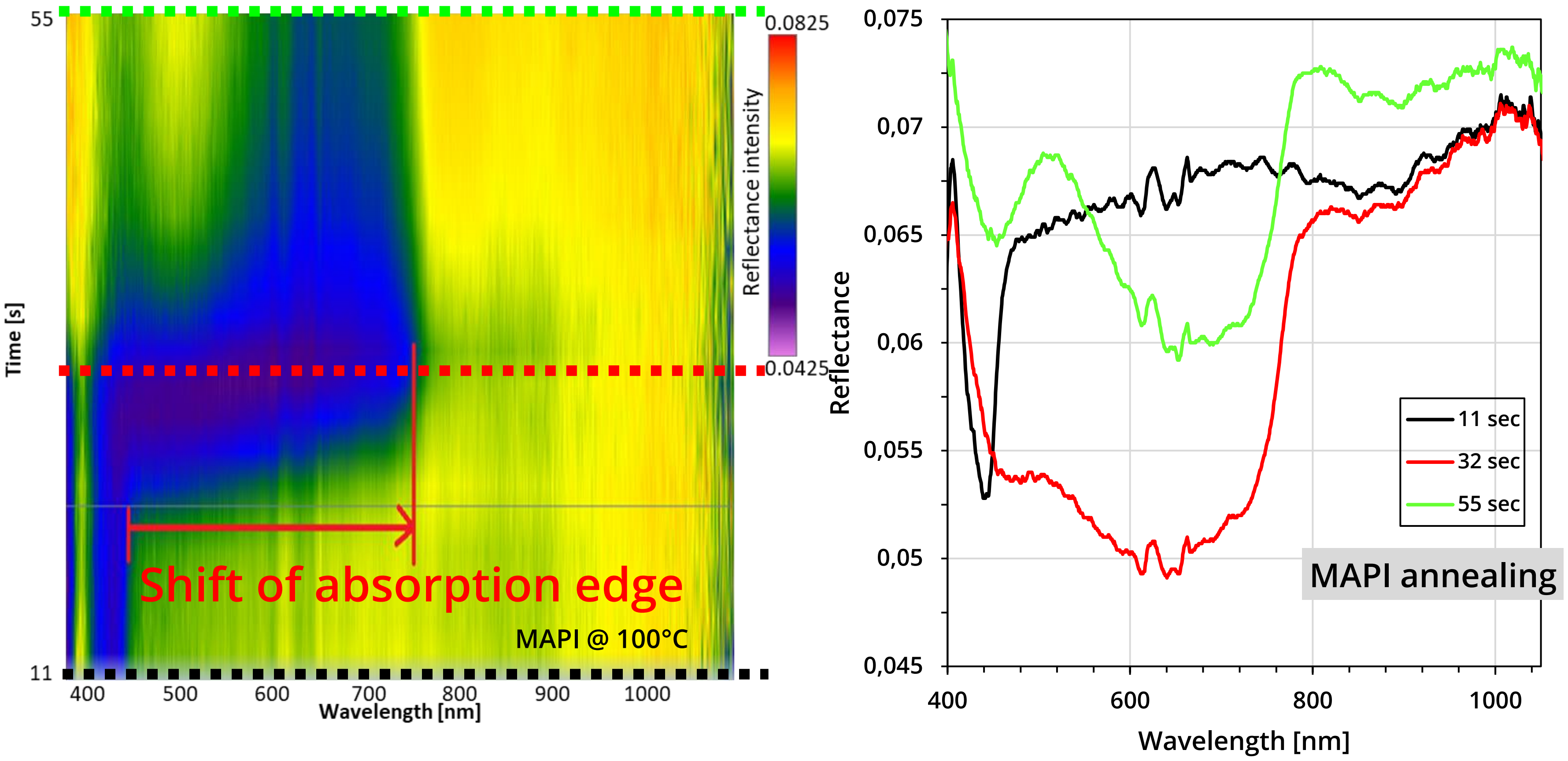
references: see last slide

Annealing: As it is NOT supposed to be…



references: see last slide

In-situ monitoring of perovskite formation

Helmholtz Zentrum Berlin
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Spin-Coating

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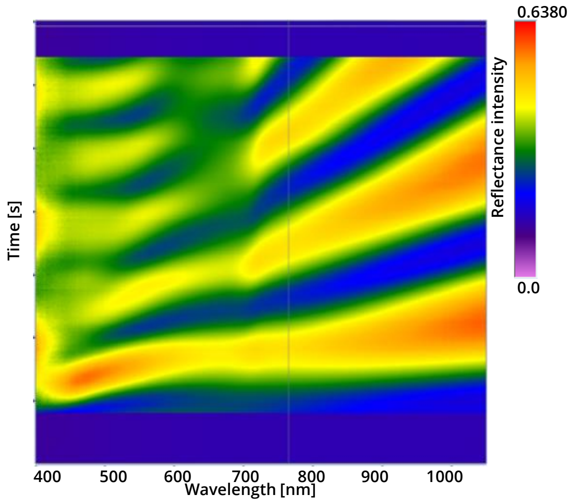
Annealing

- Band gap formation
- Film degradation by phase transitions

Thermal evaporation



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Slot-die coating

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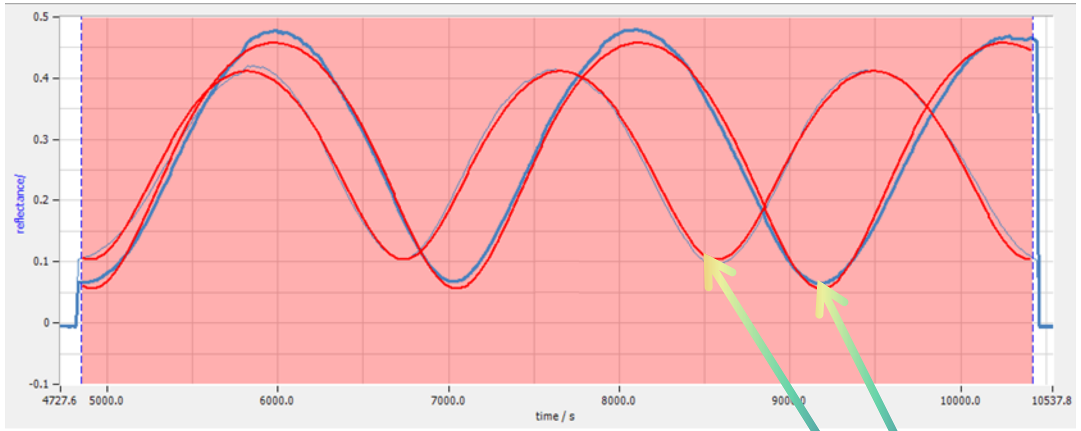
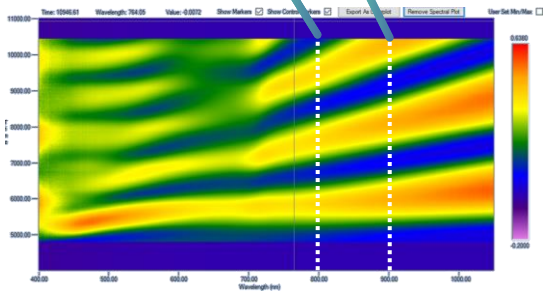
In-situ monitoring of perovskite formation…

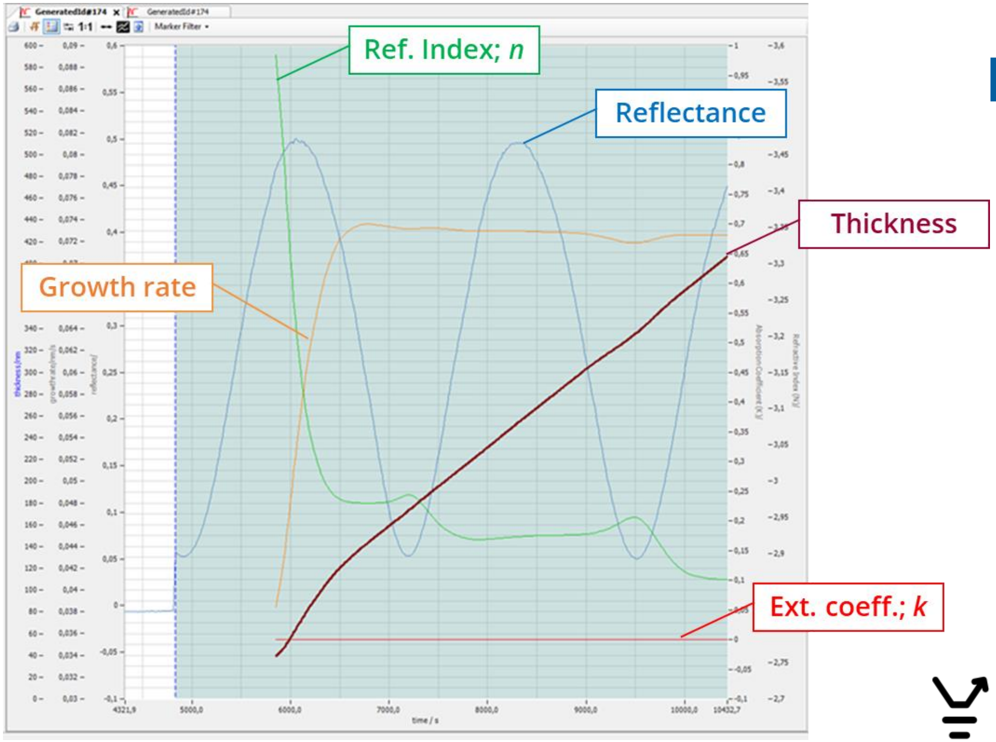
… Quantitative growth analysis…

- …by transient analysis …





- … for real-time results…



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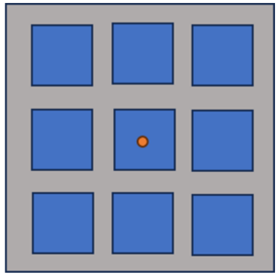
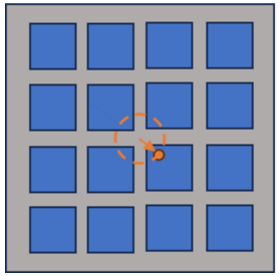
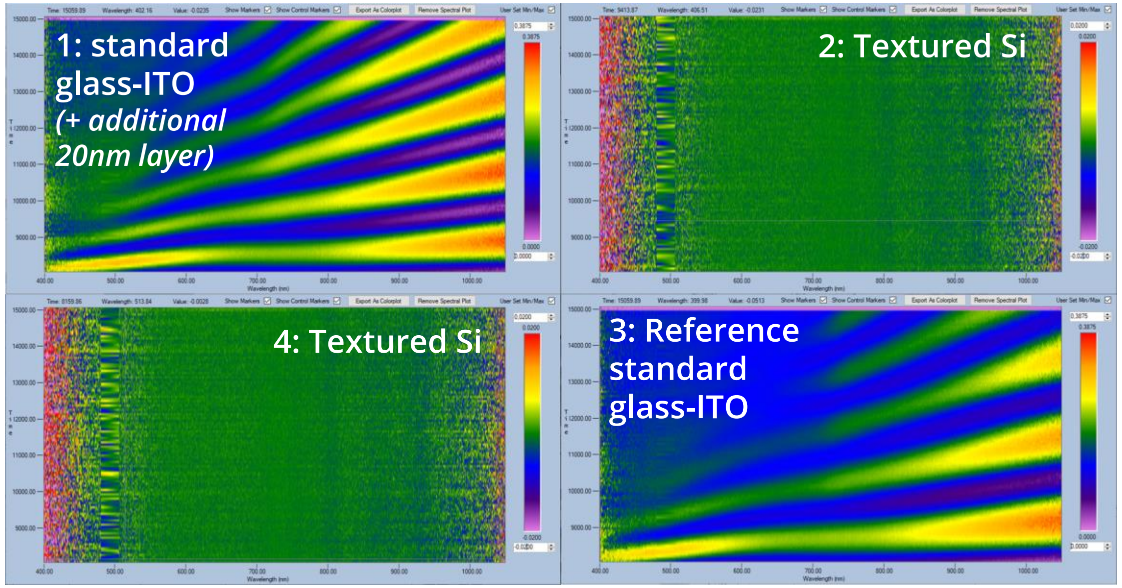
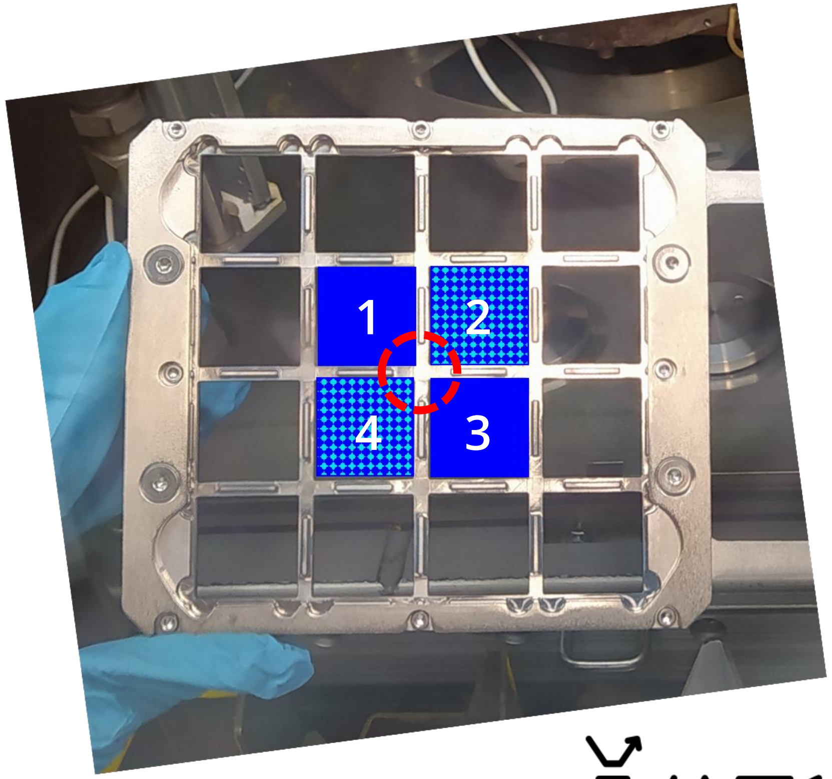
In-situ monitoring of perovskite formation…

… multi-sample analysis…









- Each sample is analyzed separately
- Comparative studies possible
- Indirect monitoring of textures samples by planar control samples
  - Almost R = 0 on textured samples
  - Full signal and "same" process on planar ones

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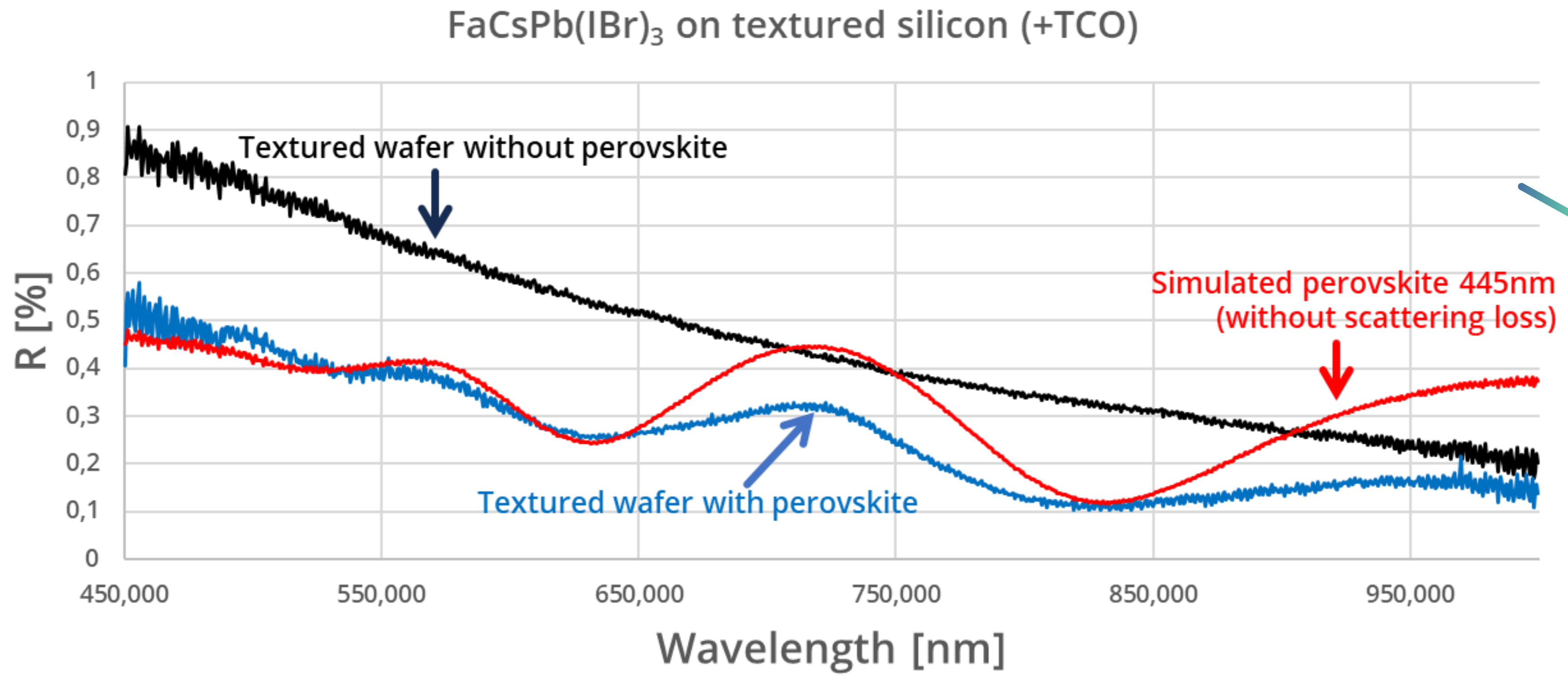
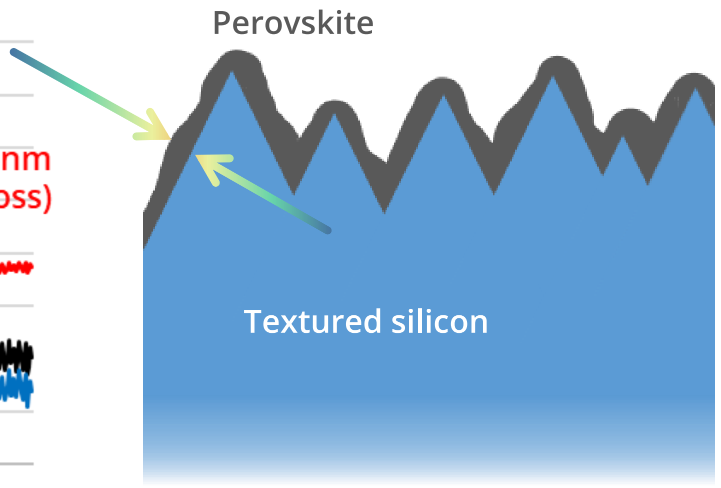
Outlook: First results with texture-optimized reflectance





- With texture optimized reflectance, perovskite thickness can be calculated → agrees with SEM thickness
- *n*,*k* was deduced from in-situ reflectance data
- Currently being implemented for in-line application

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In-situ monitoring of perovskite formation

HZB Helmholtz Zentrum Berlin
HySPRINT

Spin-Coating

- Early fringes → wet film thickness
- Late fringes → solid film thickness
- Fingerprint of reaction kinetics
- Late fringes → roughness
- Band gap formation

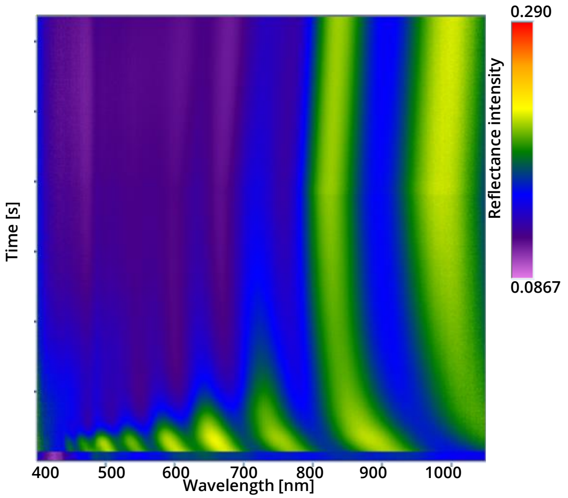
Annealing

- Band gap formation
- Film degradation by phase transitions

Thermal evaporation

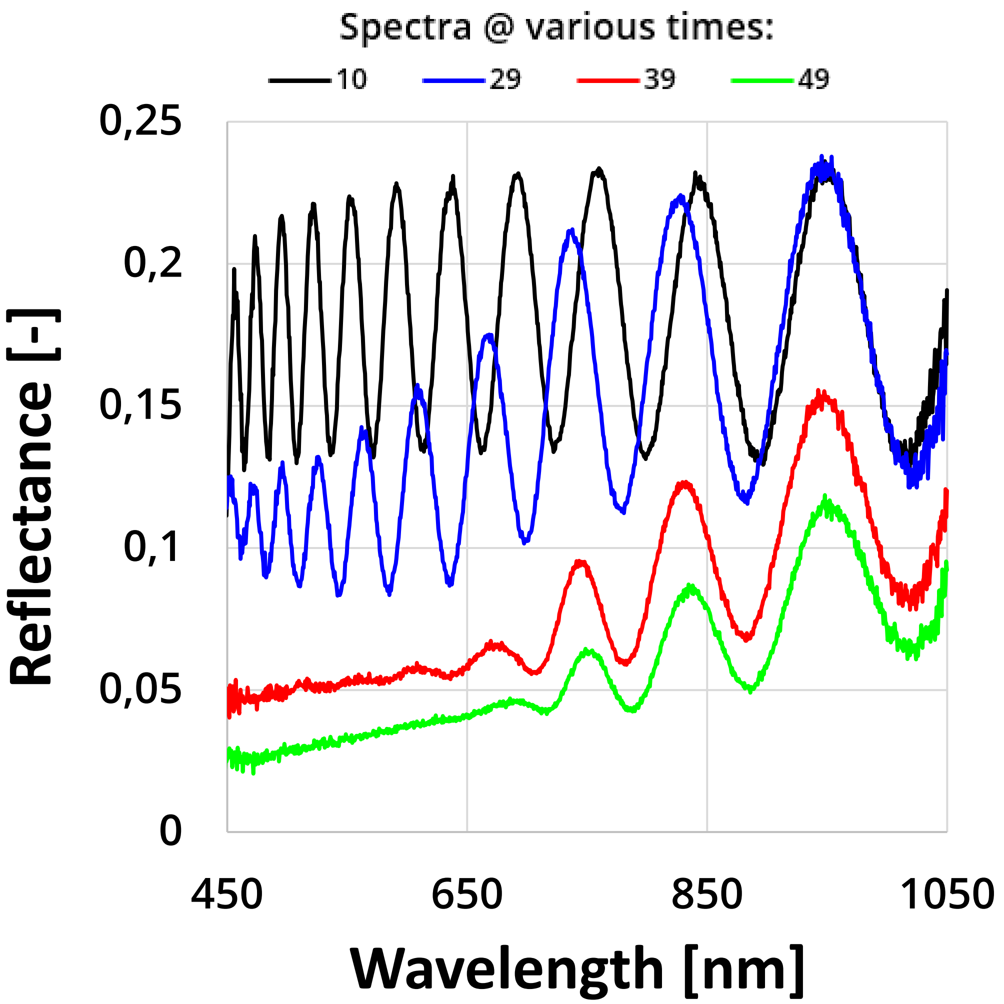
- Fringes → growth rate → thickness
- Band gap formation
- Roughness
- For const. growth rate → n,k
- For known n,k → thickness

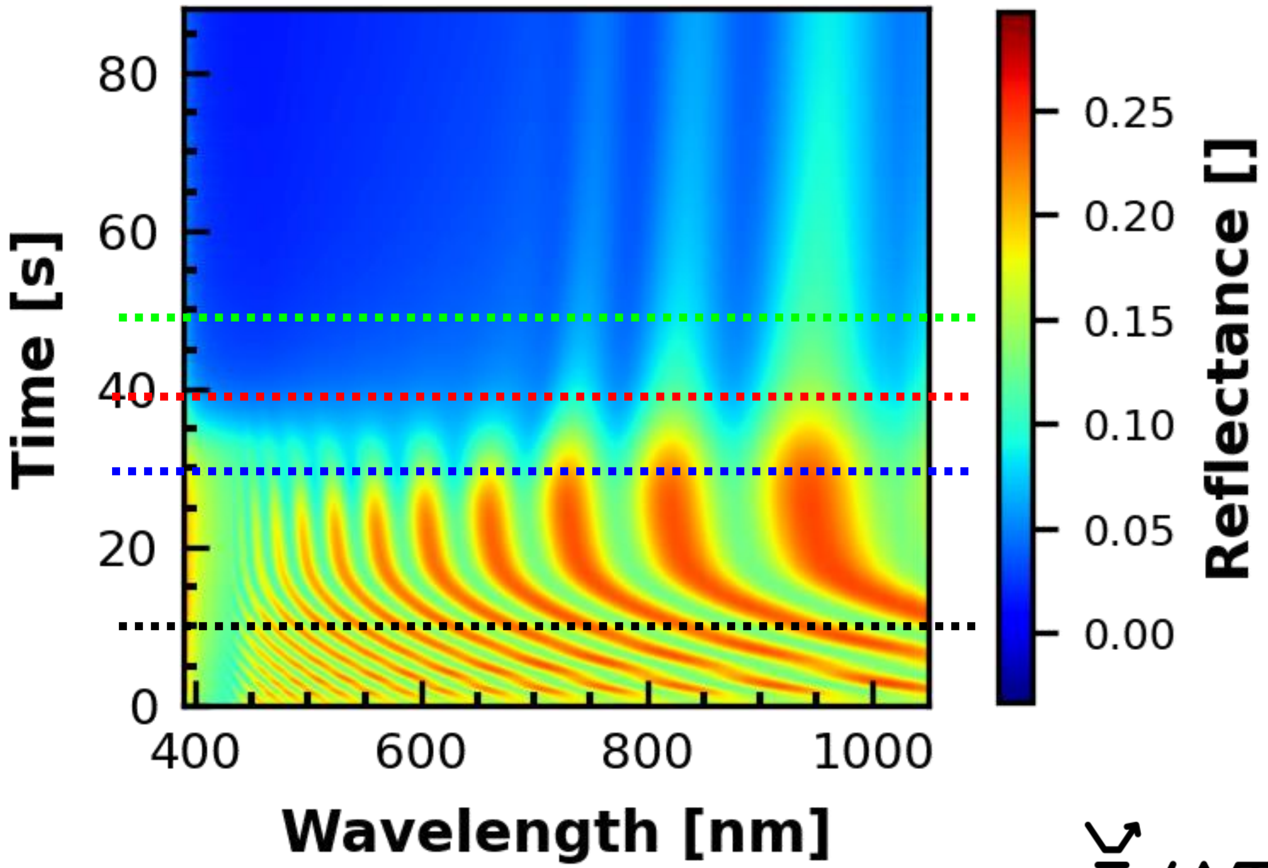
Slot-die coating



- Early fringes → wet film thickness
- Late fringes → solid film thickness
- Fingerprint of reaction kinetics
- Late fringes → roughness
- Band gap formation

Analysis of an SDC run (MAPI)

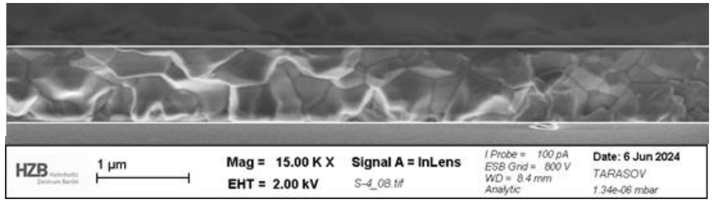


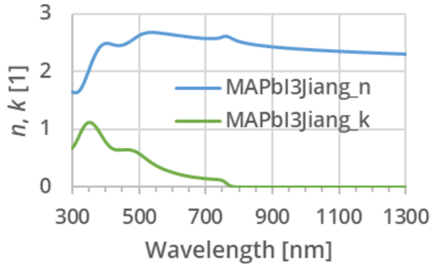


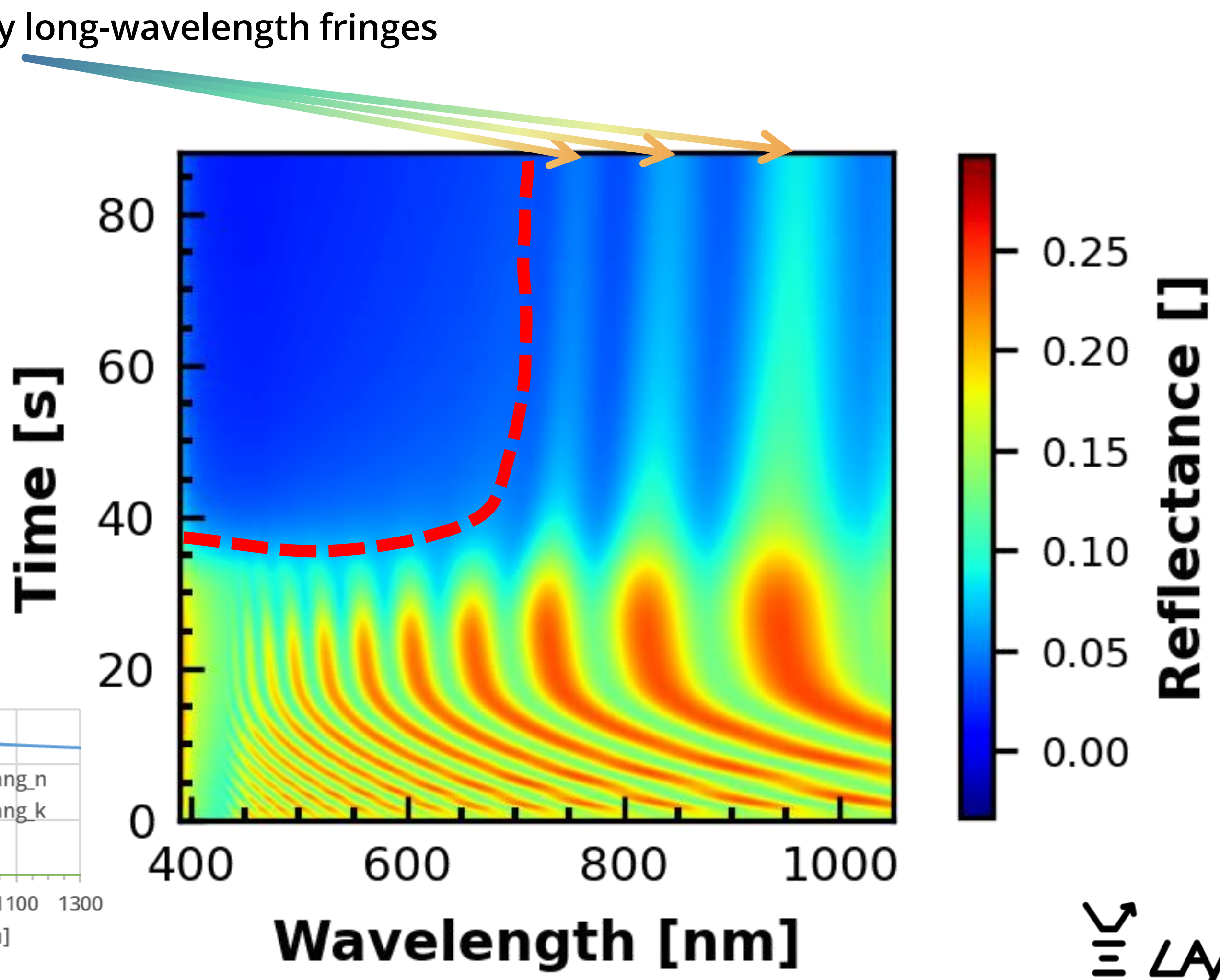
references: Harrick, 1971

Analysis of an SDC run (MAPI)

- Intensity decreasing due to roughening
- MAPI bandgap evolves
- Stationary long-wavelength fringes indicate const. thickness
- By applying solid state *n*,*k* final thickness can be calculated in good agreement with SEM
  - *d* ≈ 890 nm



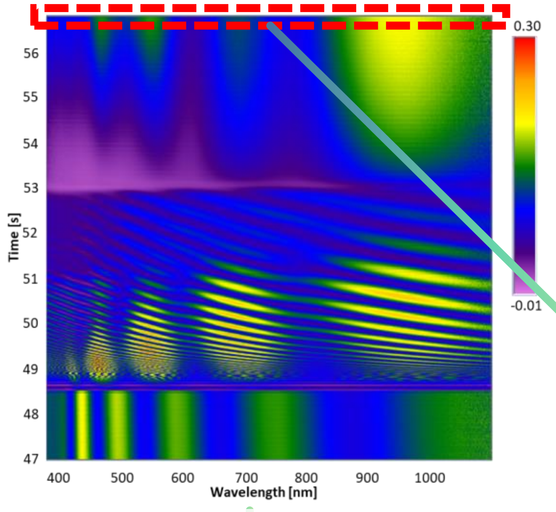




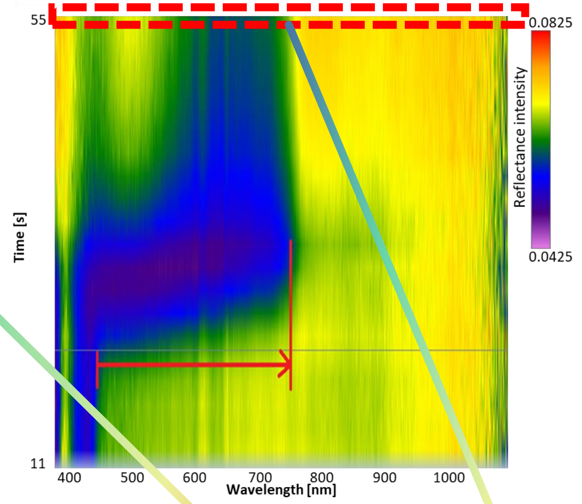
references: Harrick, 1971

In-situ monitoring of perovskite formation

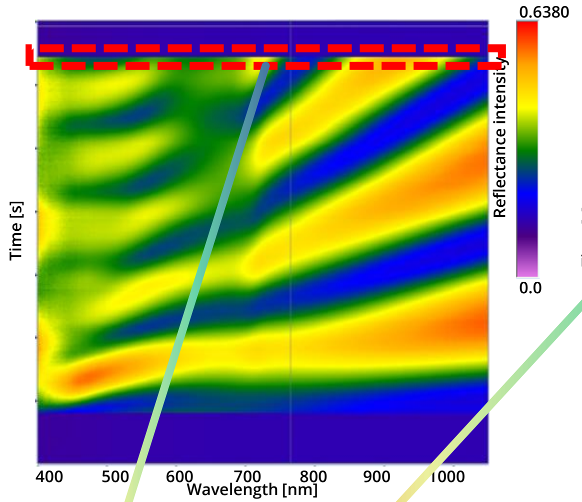
Spin-Coating



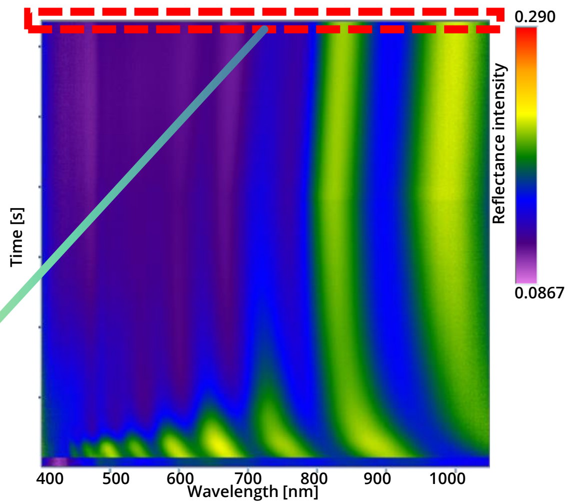
Annealing



Thermal evaporation



Slot-die coating



- Early fringes → wet film thickness
- Late fringes → dry film thickness
- Fingerprint of reaction kinetics
- Late fringes → roughness
- Band gap formation

- Band gap formation
- Film degradation by phase transitions

- Fringes → growth rate → thickness
- Band gap formation
- Roughness
- For const. growth rate → n,k
- For known n,k → thickness

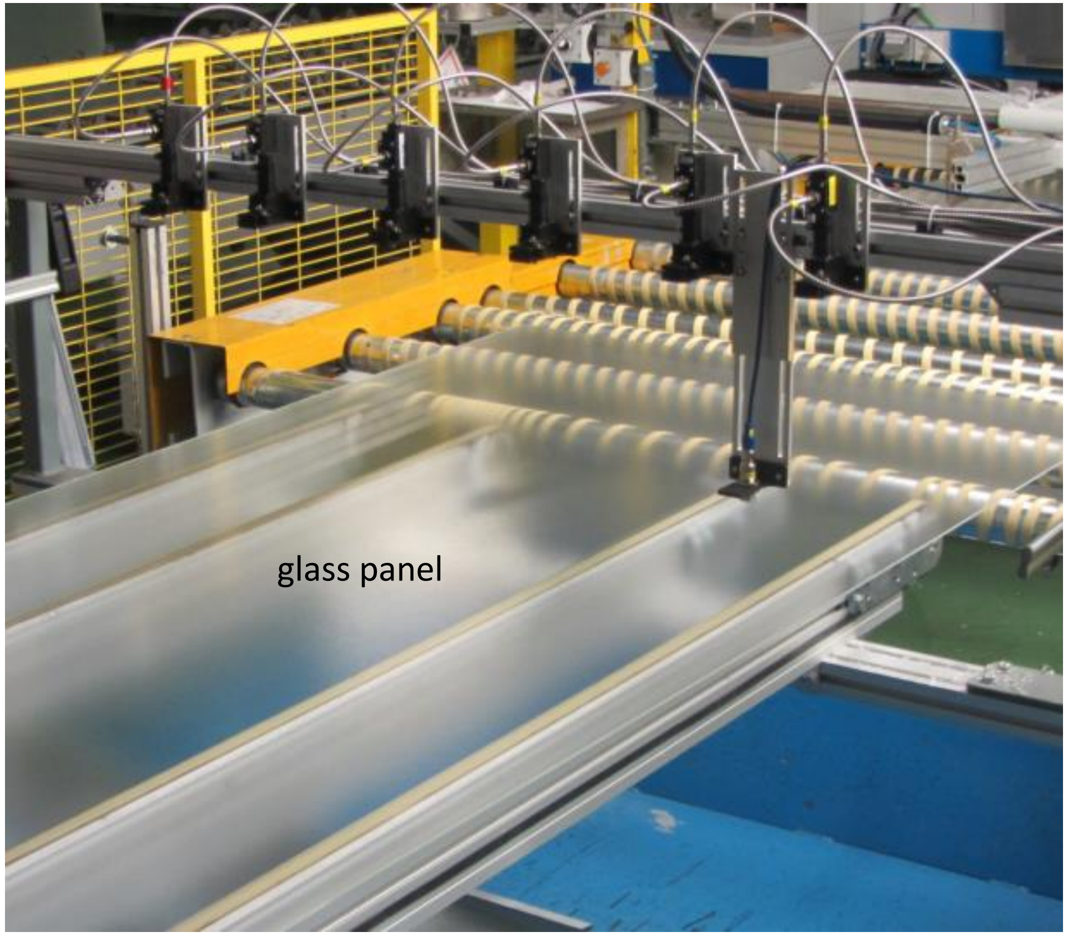
- Early fringes → wet film thickness
- Late fringes → dry film thickness
- Fingerprint of reaction kinetics
- Late fringes → roughness
- Band gap formation

In all cases, "last" in-situ spectrum corresponds to the spectrum obtained in-line

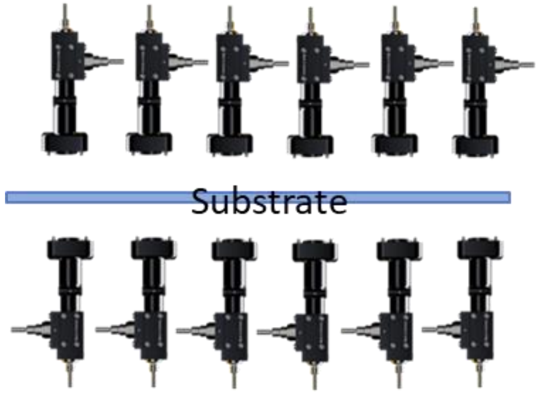
Outline

- Company introduction
- Metrology methods & monitoring parameters
- In-situ monitoring of perovskite formation
- In-line monitoring of perovskite formation
- Metrology capabilities for entire perovskite stack
- Summary & outlook

Typical in-line setups for in-line TCO monitoring

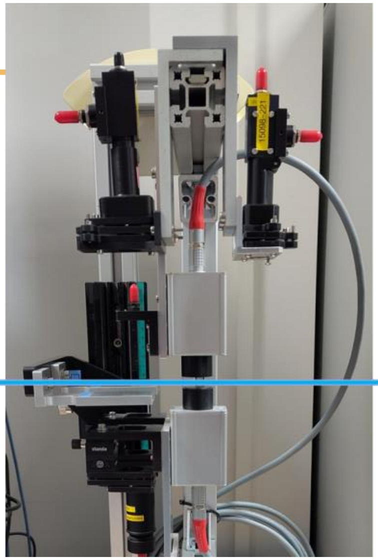


Reflectance setup for
TCO-coated glass

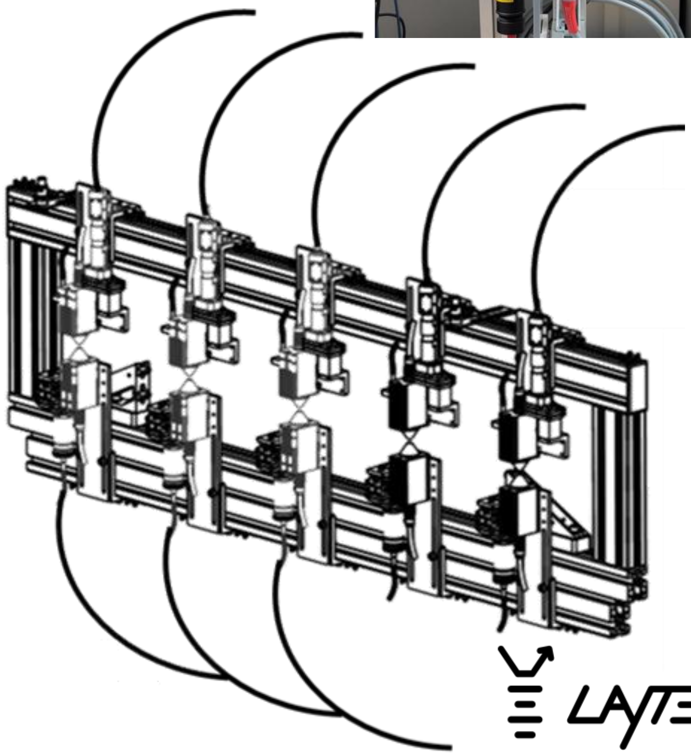


Reflectance & transmittance

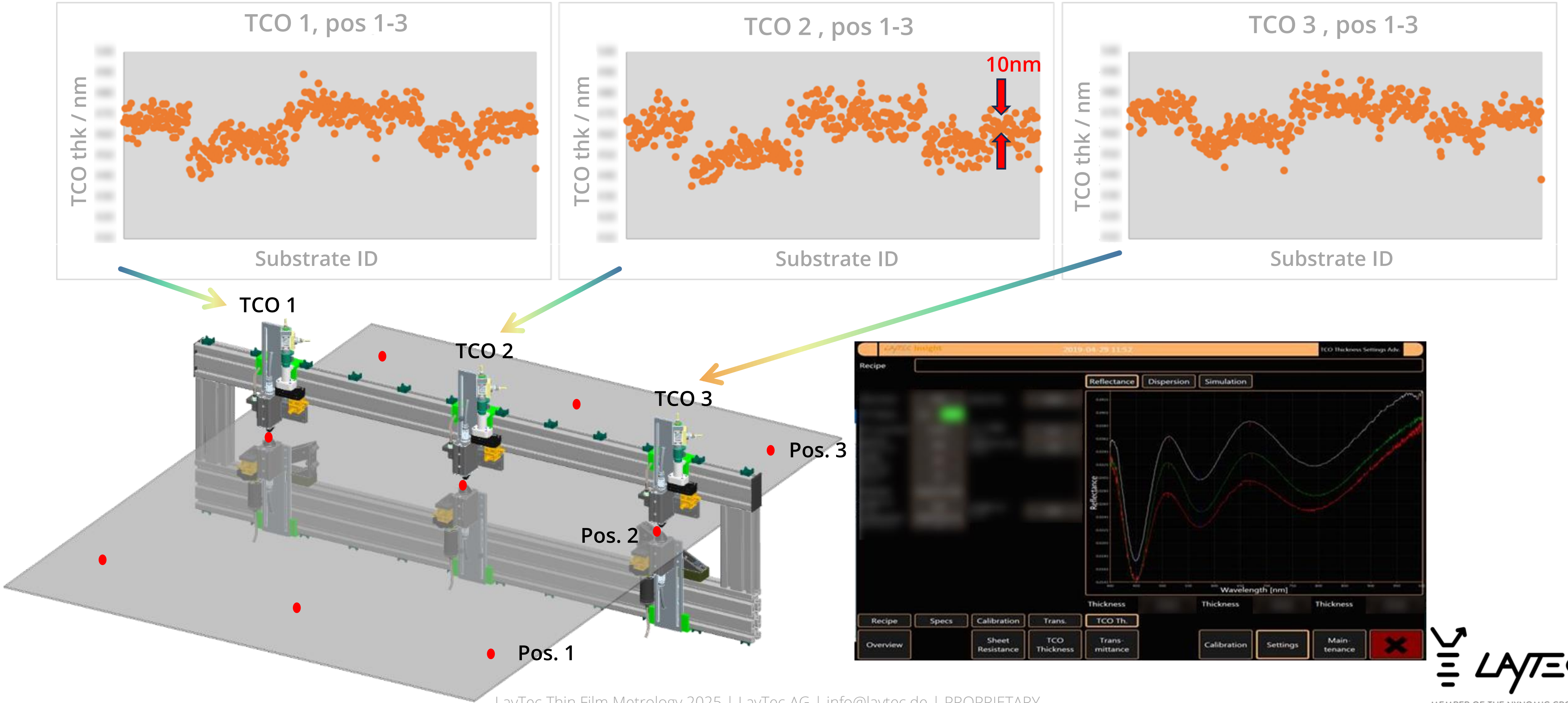
Reflectance &
transmittance &
sheet resistance



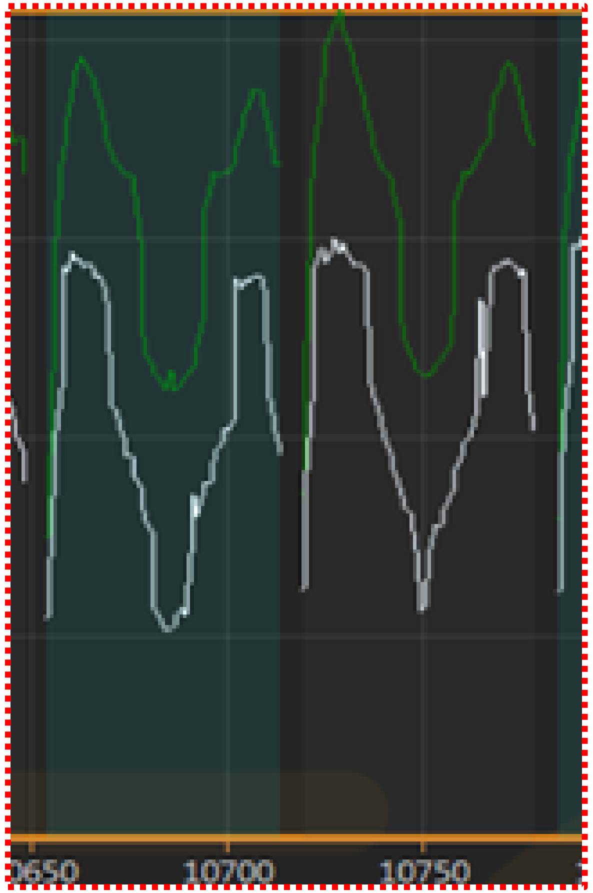
glass panel



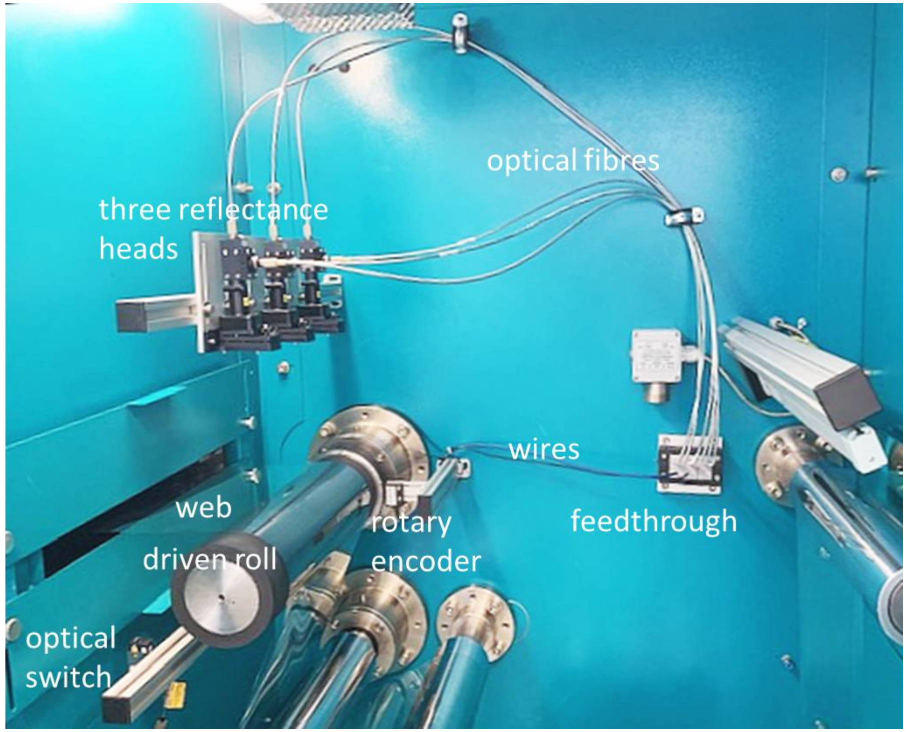
In-line monitoring of TCO / glass substrates from production



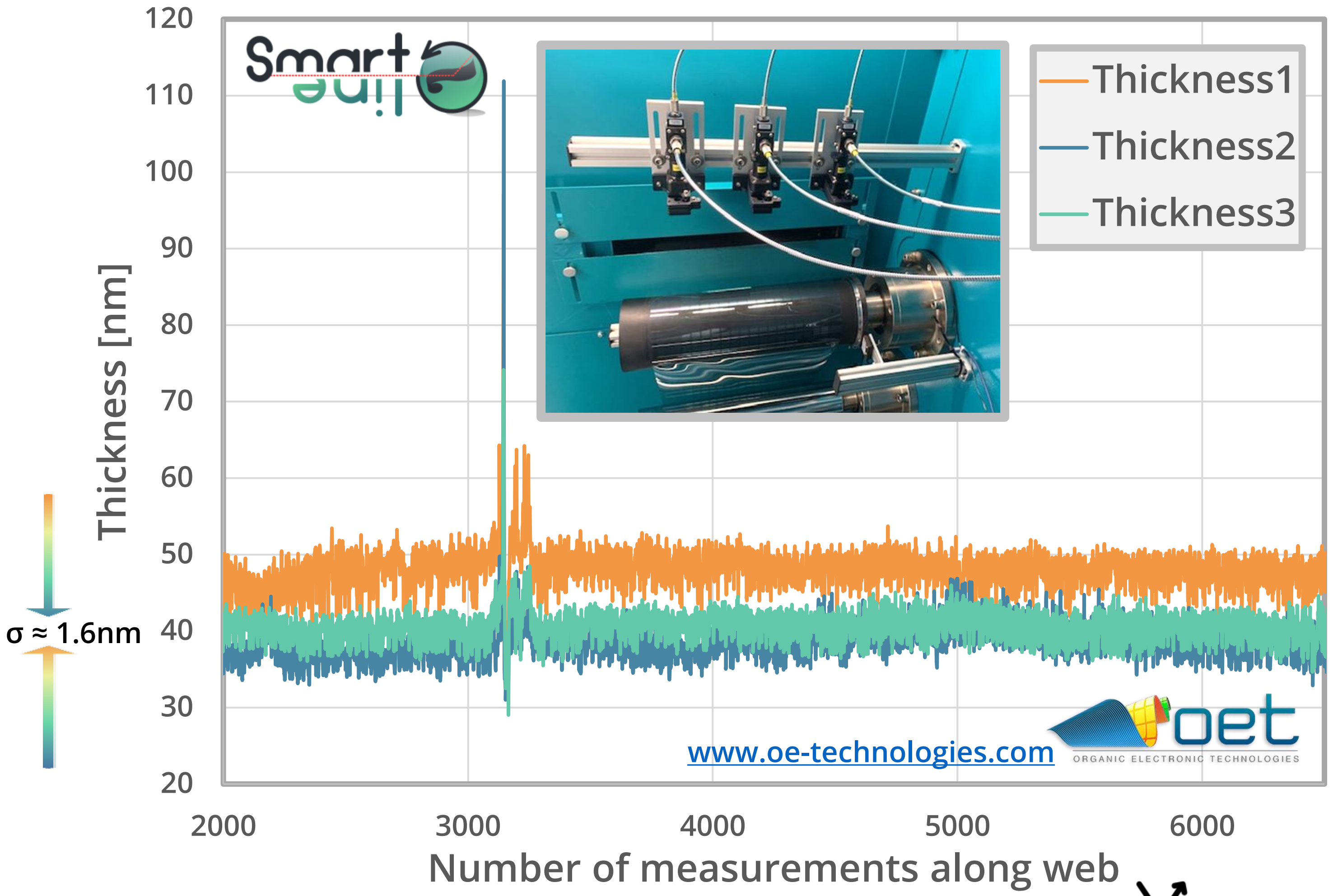
Sheet-2-sheet quality control: Exemplary production data (CIGS)



Roll-2-roll (R2R) quality control



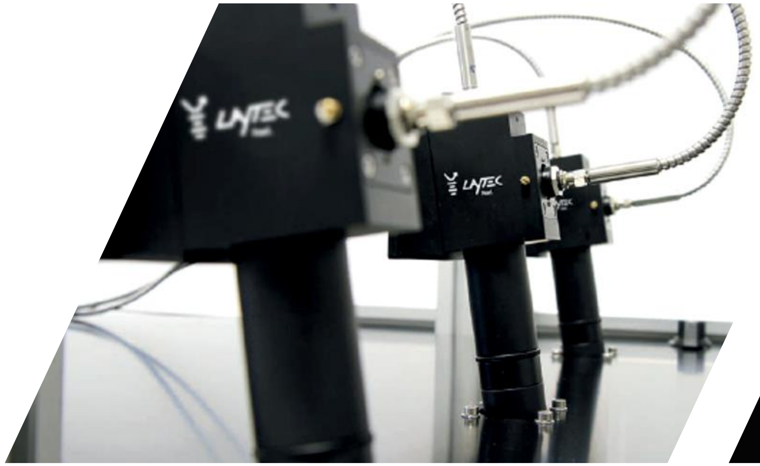
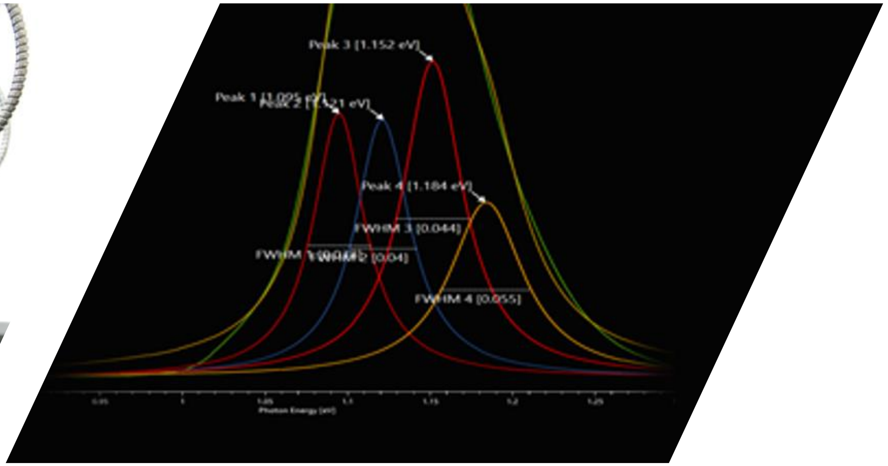
- In-line monitoring of deposition of electron-transport layer on PET / IMI (ITO-metal-ITO)

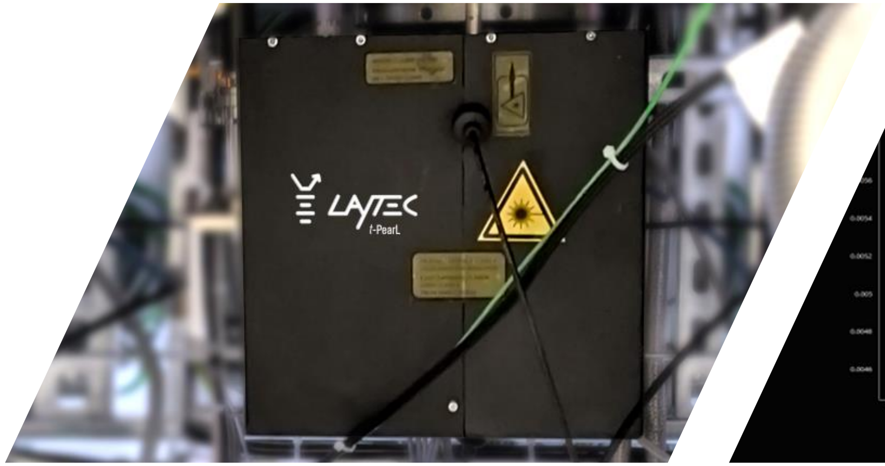


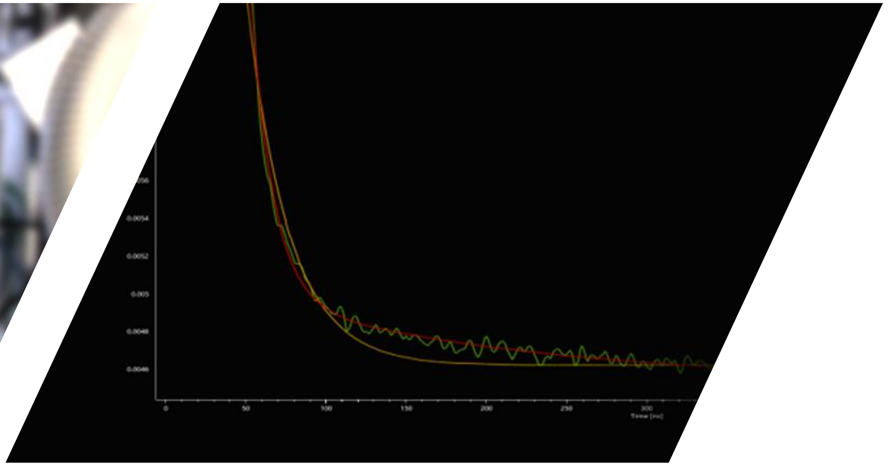
The Smartline project has received funding from the European Union's HORIZON 2020 research and innovation programme under Grant Agreement No 768707.

Photoluminescence systems

- Metrology method portfolio for photoluminescence:
- Spectral PL
  - Peak deconvolution
  - Composition
- Time-resolved PL
  - Charge carrier lifetime (> 20ns)
- Can be combined
- Laser class >3b
- Wide variety of excitation sources





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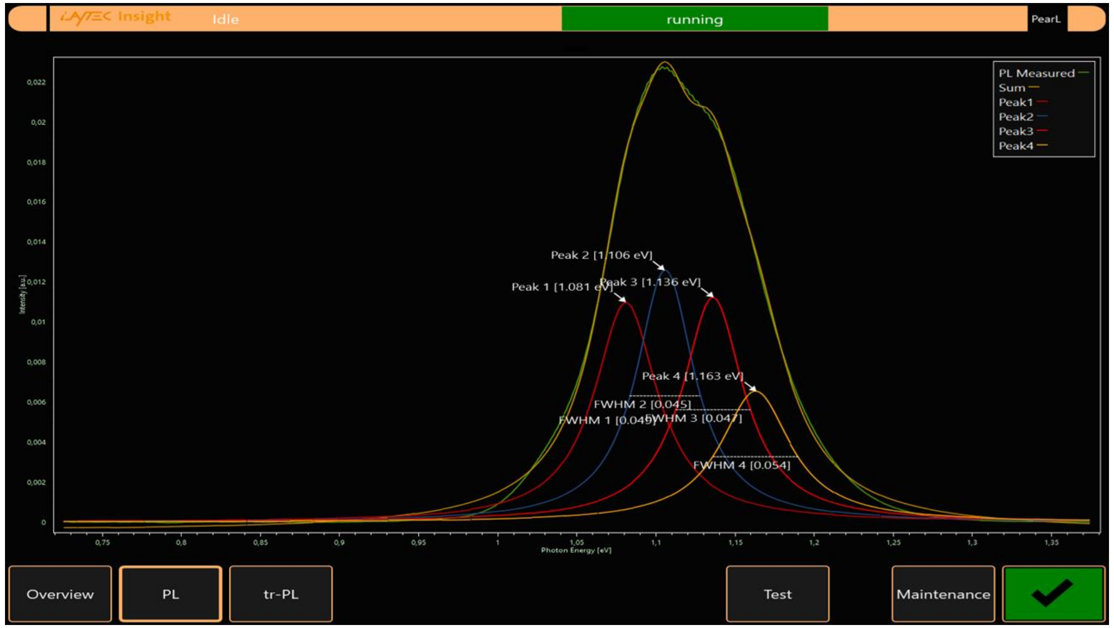
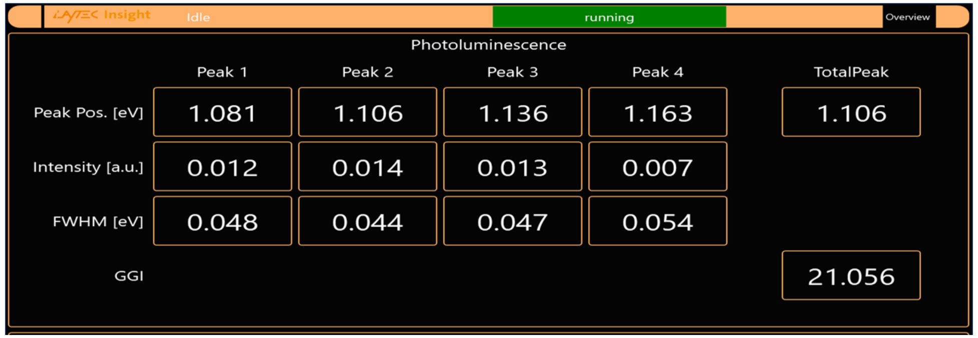
PearL – spectral PL

- Wide range of UV, VIS, NIR wavelengths
- Spectral range for detection:
  - 450nm…1050nm / 1700nm
  - 900nm… 1700nm / 2500nm
- Peak fit with up to 4 peaks
- Usually class 3b - 4 laser is needed for large working distances (vacuum)
- For short working distances, laser-free LED-based system available (slot-die coating etc.)




Insight | Idle | running | Overview

Photoluminescence

	Peak 1	Peak 2	Peak 3	Peak 4	TotalPeak
Peak Pos. [eV]	1.081	1.106	1.136	1.163	1.106
Intensity [a.u.]	0.012	0.014	0.013	0.007	
FWHM [eV]	0.048	0.044	0.047	0.054	
GGI					21.056

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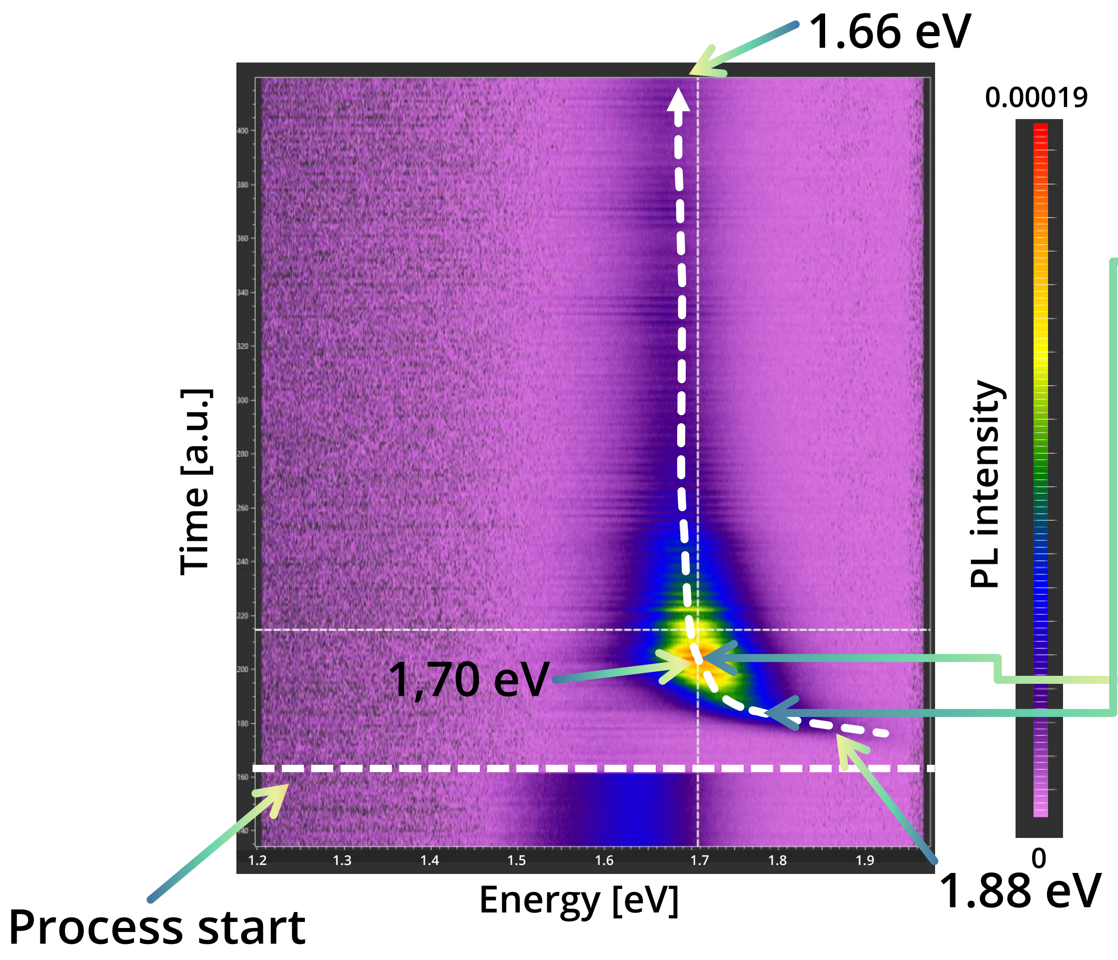
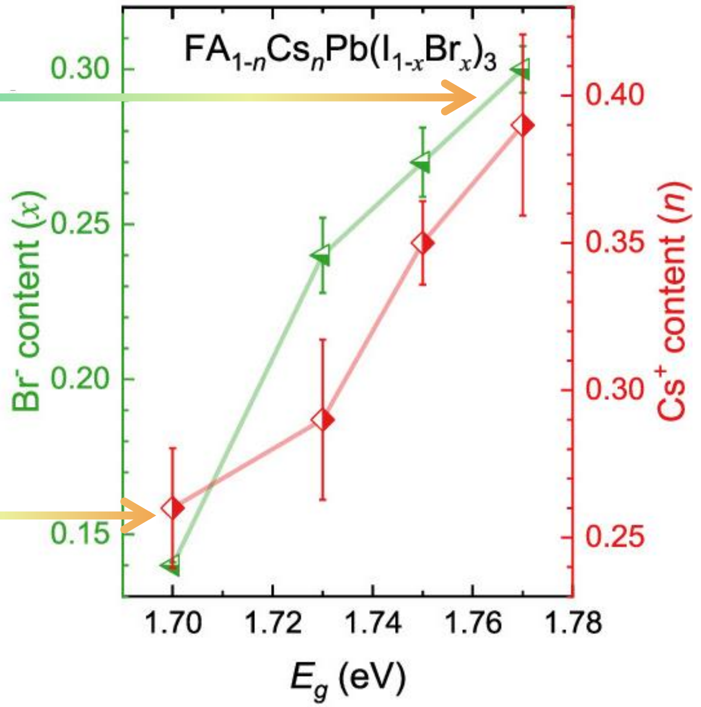
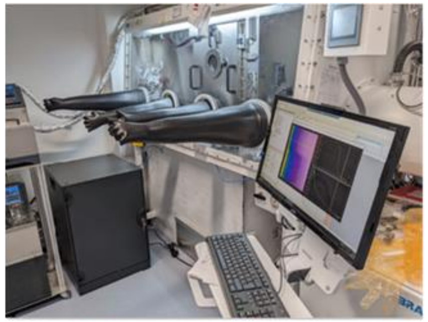
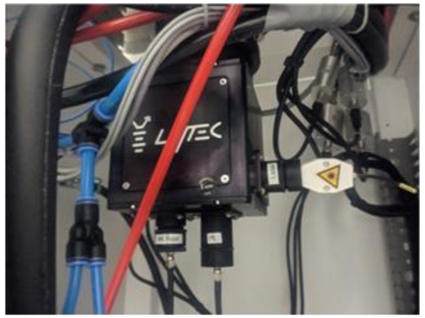
In-situ monitoring of perovskite formation during $FaCsPb(IBr)_3$ PVD: Compositional shifts



L. Gil-Escrig et al., *ACS Energy Letters* 2021 *6* (2), 827-836
DOI: 10.1021/acsenergylett.0c02445







Supported by:
Federal Ministry for Economic Affairs and Climate Action
on the basis of a decision by the German Bundestag
Partially funded by the Federal Ministry for Economic Affairs and Climate Action (BMWK) under the contract of SHAPE with the reference number of 03EE1123

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HySPRINT
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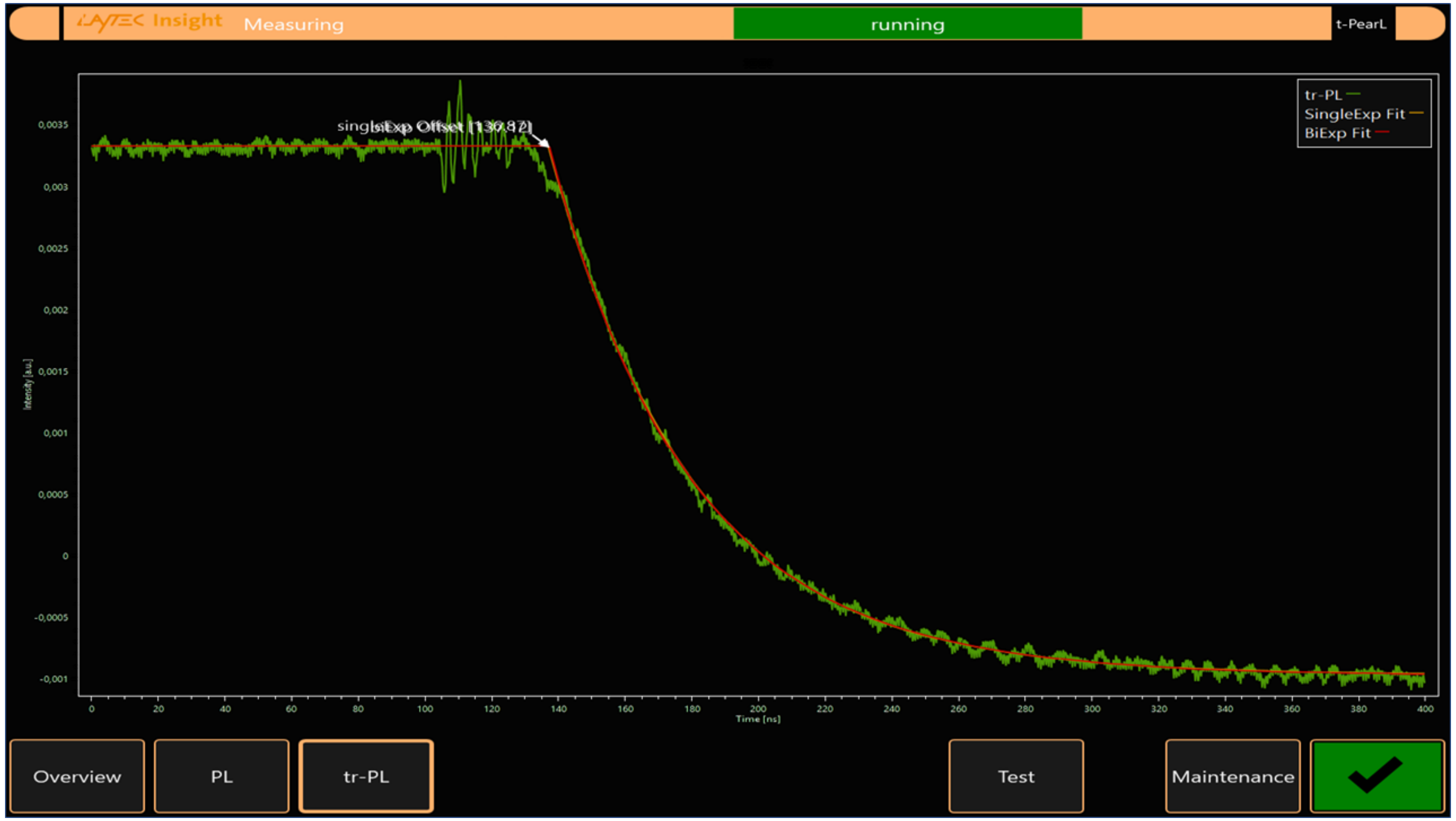
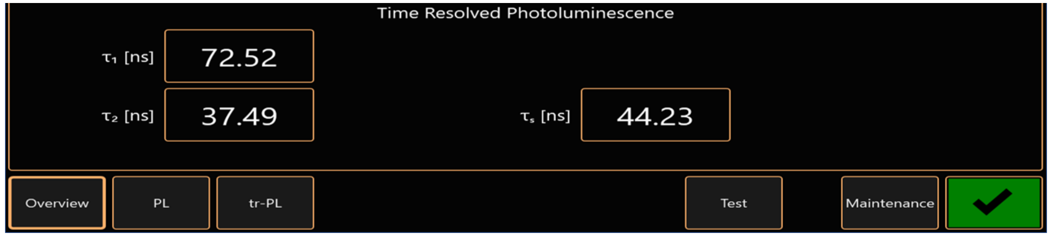
t-PearL – time-resolved PL

- Wide range of UV, VIS, NIR wavelengths
- Mono- and biexponential fit
- Lifetimes >>5ns
- Usually class 3b - 4 laser is needed





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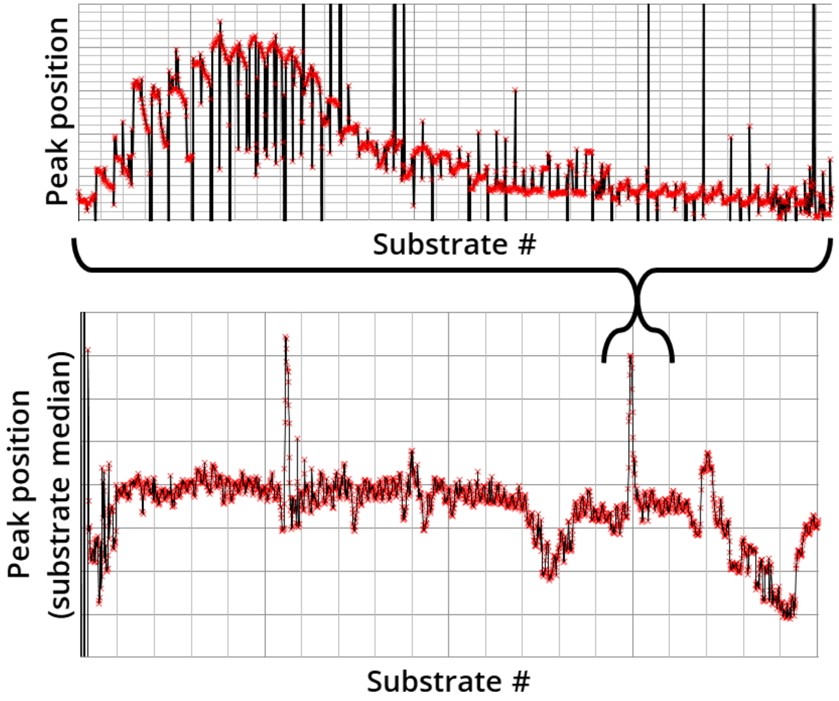
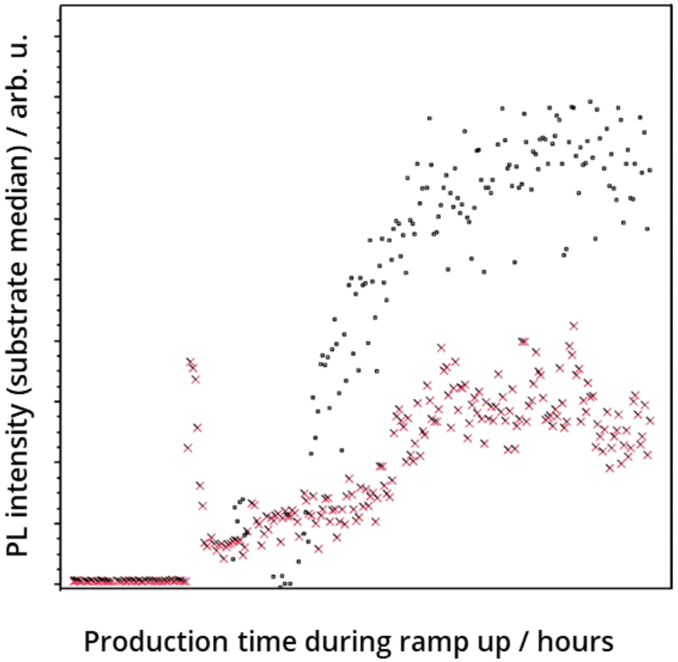
PearL – spectral PL: Exemplary production data (CIGS)

- PearL system installed in a CIGS PVD production line



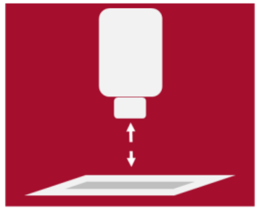


Sheet Resistance Measurement by Eddy Current Inspection

Technology

- Relies on non-contact current induction and electromagnetic field measurement
- High sample rate, high sensitivity, non-contact, dedicated to conductive materials

Non-contact
Non-destructive



Single and Multilayer Systems

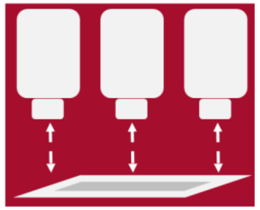
Sample Rate for
Volume Manufacturing

1,000's
measurements/sec

High Repeatability
and Bias

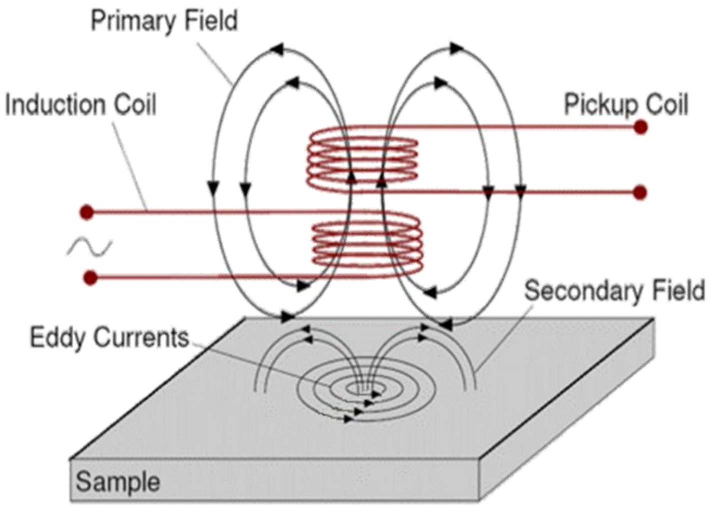
Low σ

Easy Scalability and
Integration into Tools



Vacuum and Atmospheric
processing

Dry
&
Wet



+ High sample rate
+ High sensitivity
+ Non-contact solutions
– Limited to conductive materials

Non-contact Eddy Current Testing for Glass Technology

Portable Testing

Single-Point Measurement

Mapping Solutions

Inline / Tool Integrated

- Real time high-speed measurement – up to 1,000 measurements/sec
- Scalable fixed sensor installation
- Process control in atmosphere or in vacuum environments
- Long term stability by temperature compensated measurements
- Integration of 1 – 99 monitoring lanes per system

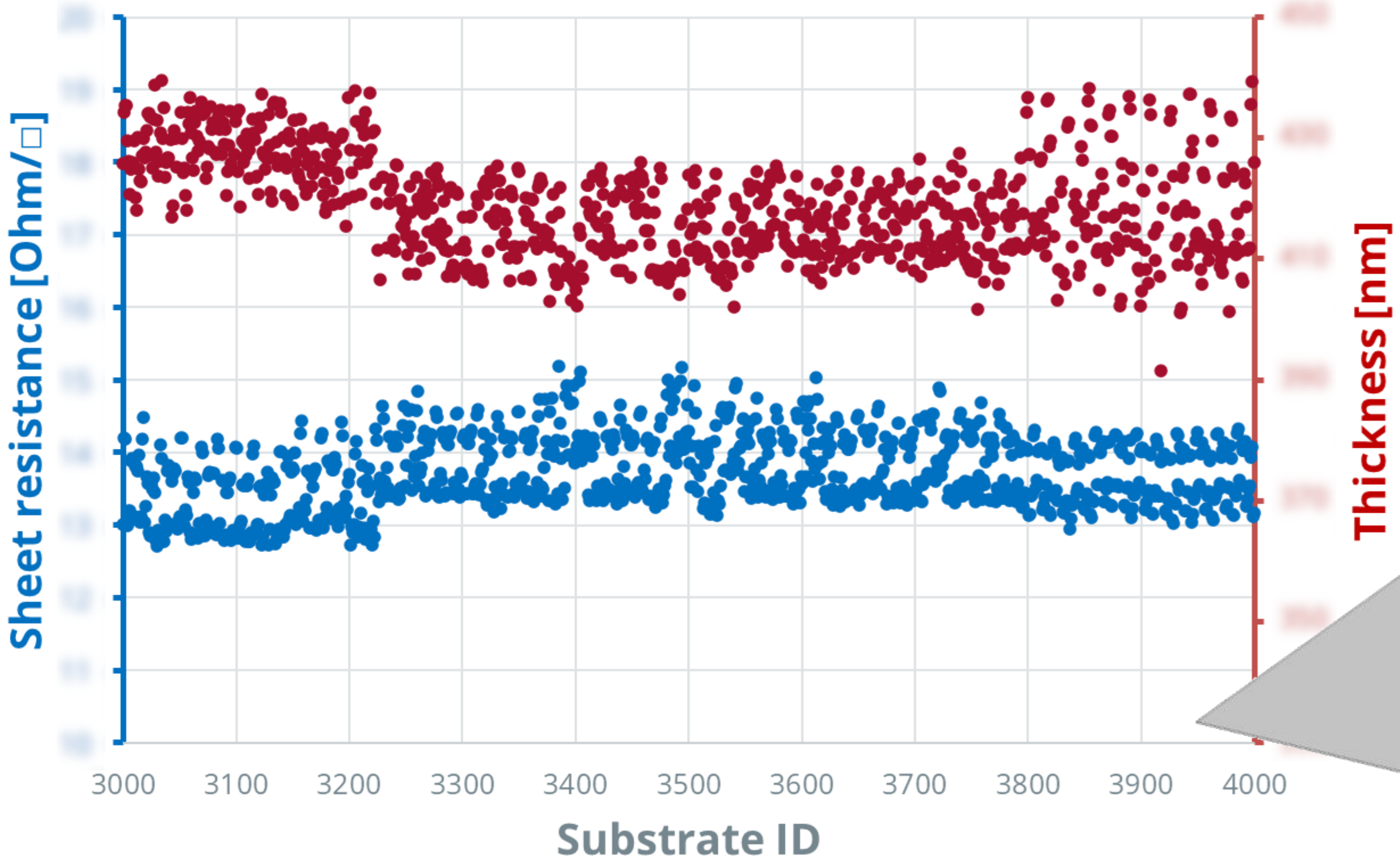
Non-contact Eddy Current Testing for Glass Technology

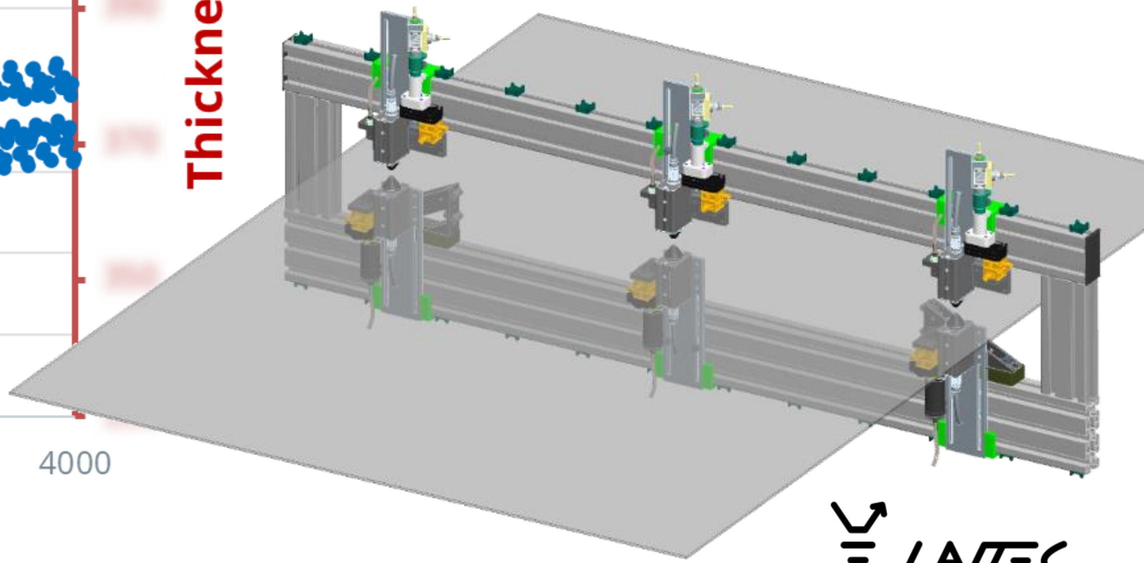
Portable Testing | Single-Point Measurement | Mapping Solutions | Inline / Tool Integrated

Suragus‘ Eddy-current systems can be fully integrated into LayTec‘s FLAMES metrology systems

- Real time high-speed measurement – up to 1,000 measurements/sec
- Scalable fixed sensor installation
- Process control in atmosphere or in vacuum environments
- Long term stability by temperature compensated measurements
- Integration of 1 – 99 monitoring lanes per system

Combined thickness & sheet resistance monitoring (ITO)





Outline

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- In-situ monitoring of perovskite formation
- In-line monitoring of perovskite formation
- Metrology capabilities for entire perovskite stack
- Summary & outlook

Metrology capabilities for entire perovskite stack

- **Get full insight on your perovskite devices!**
  - Anode, Cathode: Thickness, color, transmittance, sheet resistance
  - HTL, ETL: Thickness
  - Perovksite: Thickness, E_{Gap}, roughness

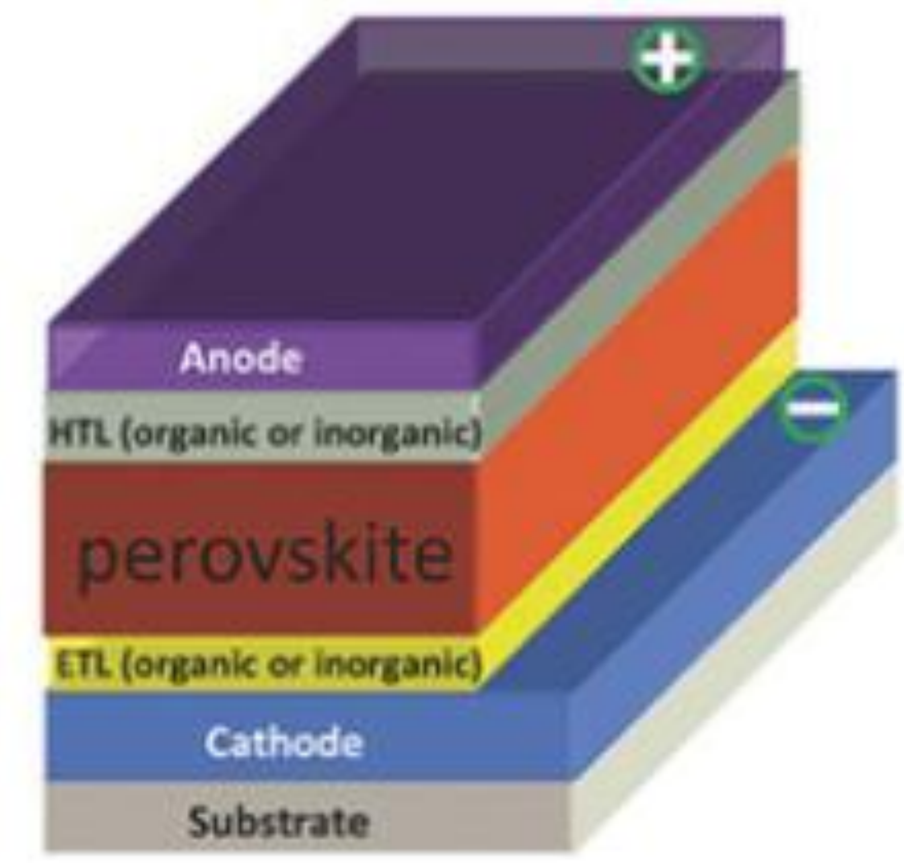

Image credits: Zhuang et al., 10.1007/s40820-023-01046-0

Outline

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Summary & outlook

- Broad spectrum of technologies based on 25 years of in-situ and in-line metrology
- Optical methods are ideally suited for monitoring perovskite formation and related layers in-situ and in-line
- Reflectance spectroscopy allows to assess film thickness, roughness, band gap and many more parameters
- Photoluminescence provides further insights about composition and lifetime
- All methods can be combined freely in one system; Eddy-current can be added for sheet resistancemeasurements
- In-situ monitoring allows for understanding 100% of the process; in-line monitoring allows for 100% production control

Knowledge is key

扫一扫上面的二维码图案，加我为朋友。

DK

塔珂机电

www.laytec.de

LAYTEC

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Acknowledgements

- The Smartline project has received funding from the European Union's HORIZON 2020 research and innovation programme under Grant Agreement No 768707
- The SHAPE project has received funding from the Federal Ministry for Economic Affairs and Climate Action under Grant Agreement No 03EE1123D
- The Solar TAP project received funding from the Helmholtz Association
- HZB groups headed by E. Unger, S. Albrecht and N. H. Nickel
- ZSW group headed by S. Paetel
- All colleagues at LayTec AG

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Federal Ministry for Economic Affairs and Climate Action
on the basis of a decision by the German Bundestag

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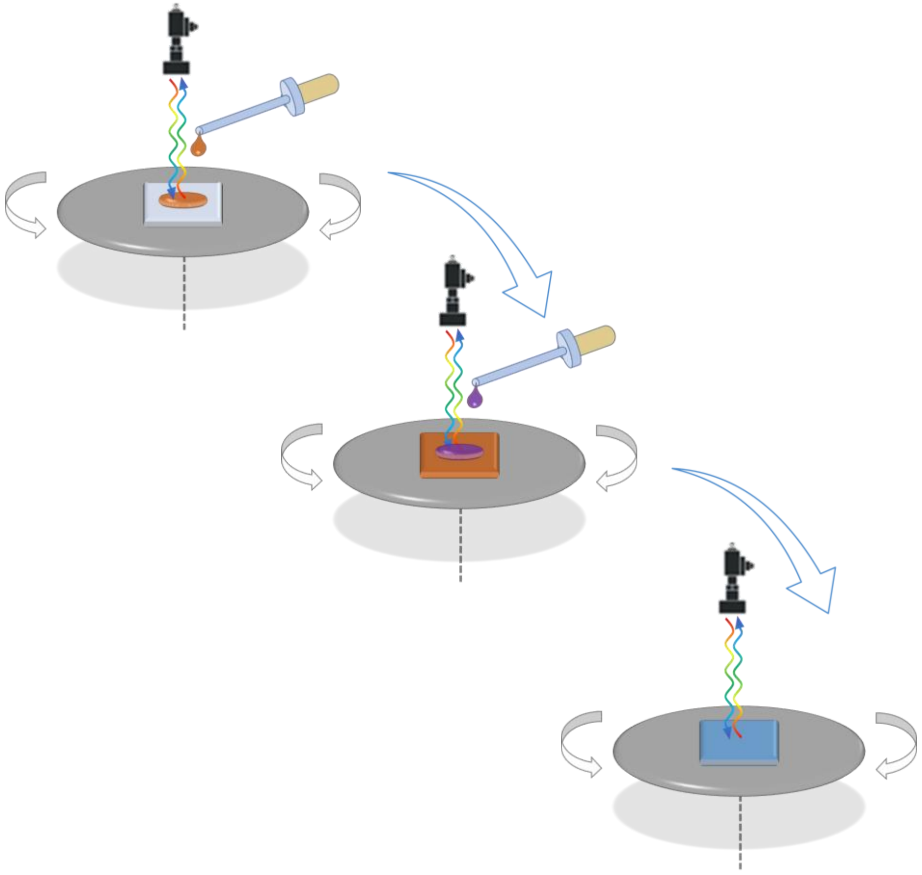
Background: Anti-Solvent Drip



- Initiation of perovskite crystallization
- Anti-solvent:
  - (partially) miscible with the solvent
  - perovskite precursor species are insoluble
- Local region of super-saturation on surface of liquid precursor by:
  - a) excess of a solvent in which the perovskite is insoluble
  - b) removing precursor solvent molecules
- Results in dense and uniform perovskite films.
- Timing is critical for perovskite morphology and device efficiency
- Crystallization is crucial for layer and device quality