Optical metrology for energy production

Dr. Nasim Rezaei

Material modelling scientist

LAYTEC

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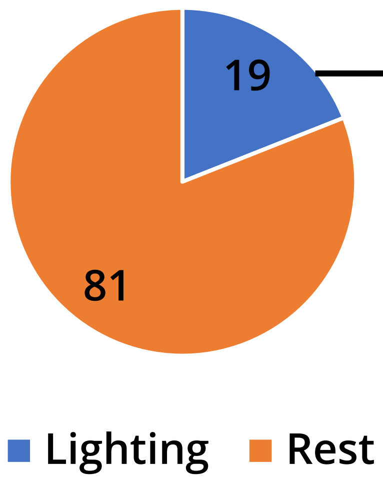
Outline

Outline

Interesting fact,1: solid-state lighting

Electricity production
2010

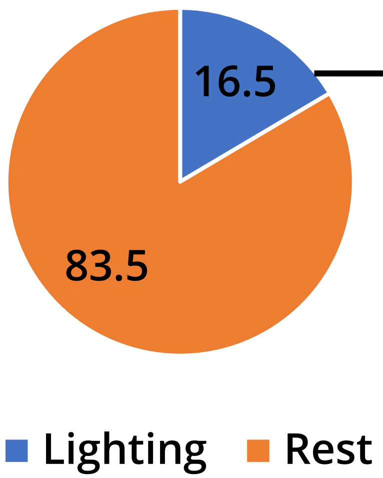


2651 TWh

Solid-state lighting

SSL

Electricity production
2021



2900 TWh

Thanks to the increase in efficiency and yield of SSL: ⇒ **For 800 lm**

- **Incandescent lamp: 60 W**
- **LED: 7-10 W**

The rebound effect?
Not there yet ☺

* G. Zissis et al., Update on the Status of LED-Lighting world market since 2018, EUR 30500 EN, Publications Office of the European Union, Luxembourg, 2021
** https://www.takethreelighting.com/lumen-watt-comparison.html

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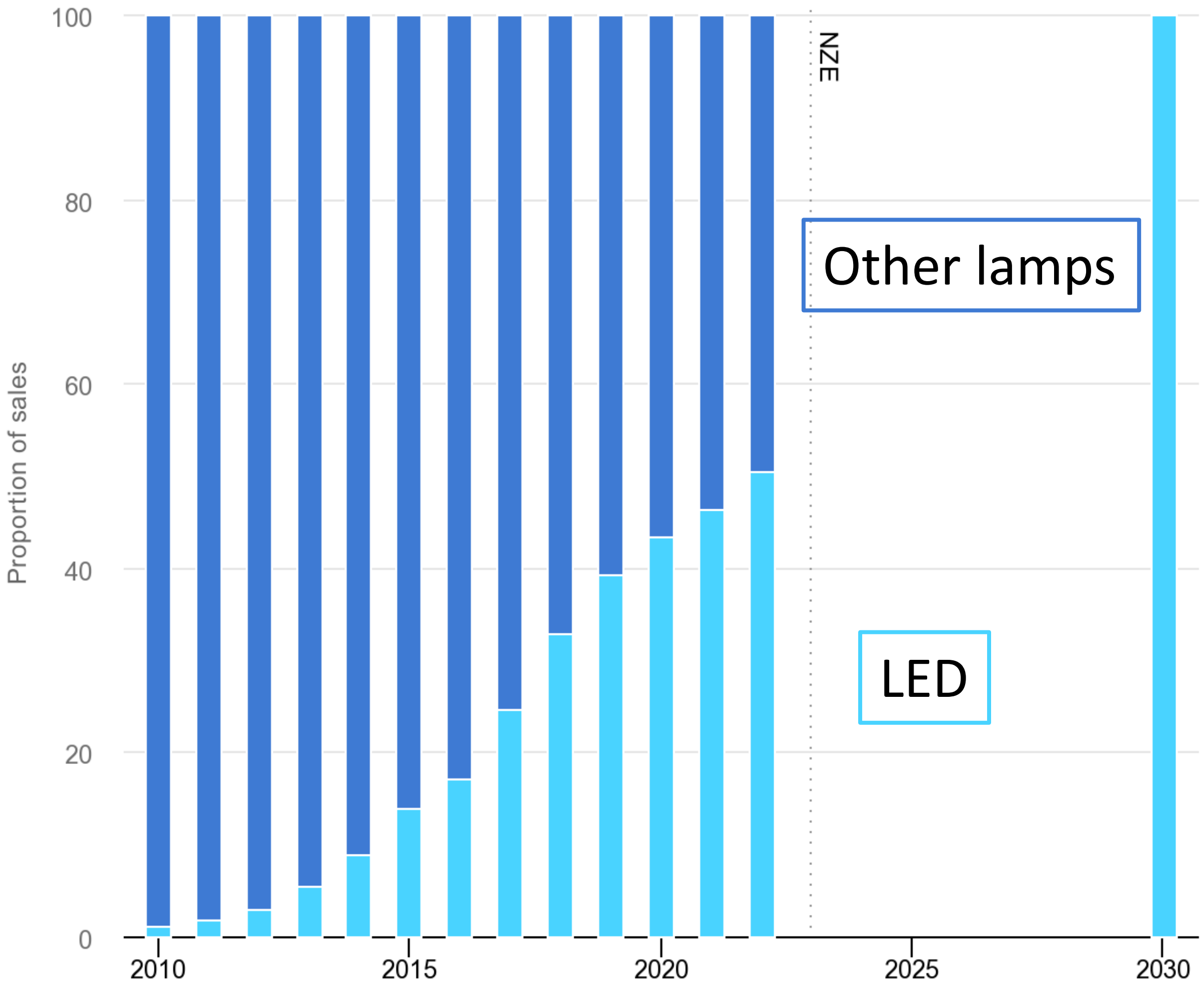
Interesting fact,1



[*]

- Lighting is not neutral in terms of human health → Wavelength matters!
  - Filtering harmful wavelengths
  - Specific applications, e.g. UV for medical use
  - Uniformity

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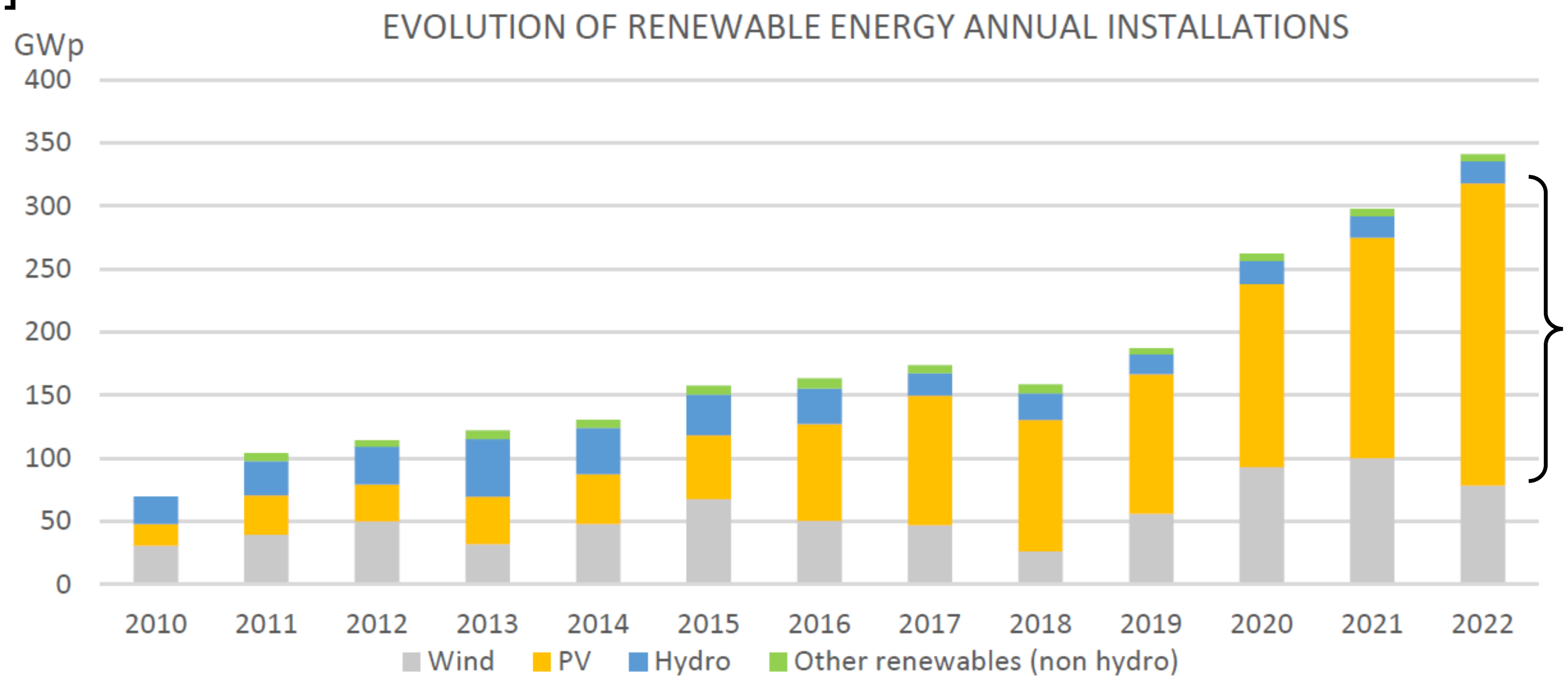
* IEA, *Global residential lighting sales share by technology in the Net Zero Scenario, 2010-2030*, IEA, Paris

Interesting fact,2: Photovoltaic technology

[*]



PV plays a major role in energy transition

- Consistent costs, technical performance and accessibility
- Faster permitting procedures

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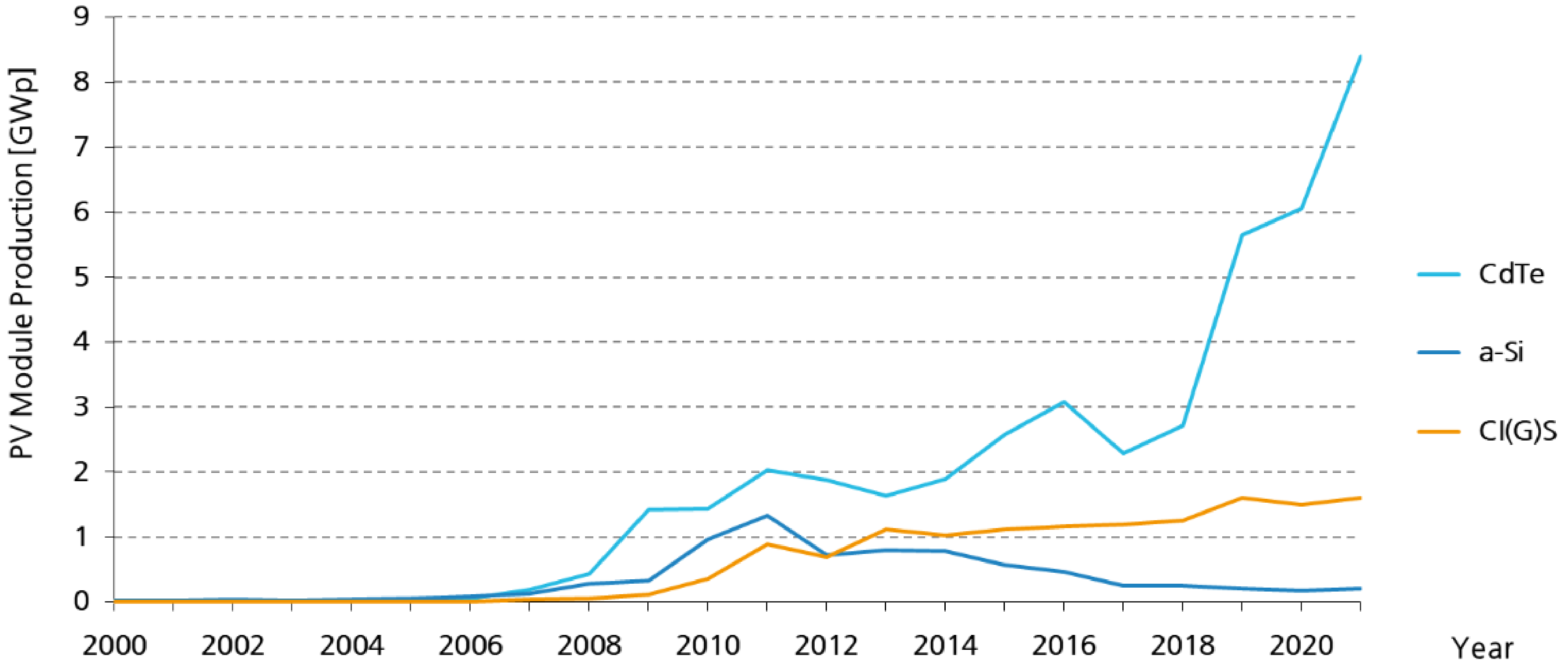
* IEA, *Snapshot of global PV markets 2023, ISBN 978-3-907281-43-7*

Interesting fact,2: Thin-film PV

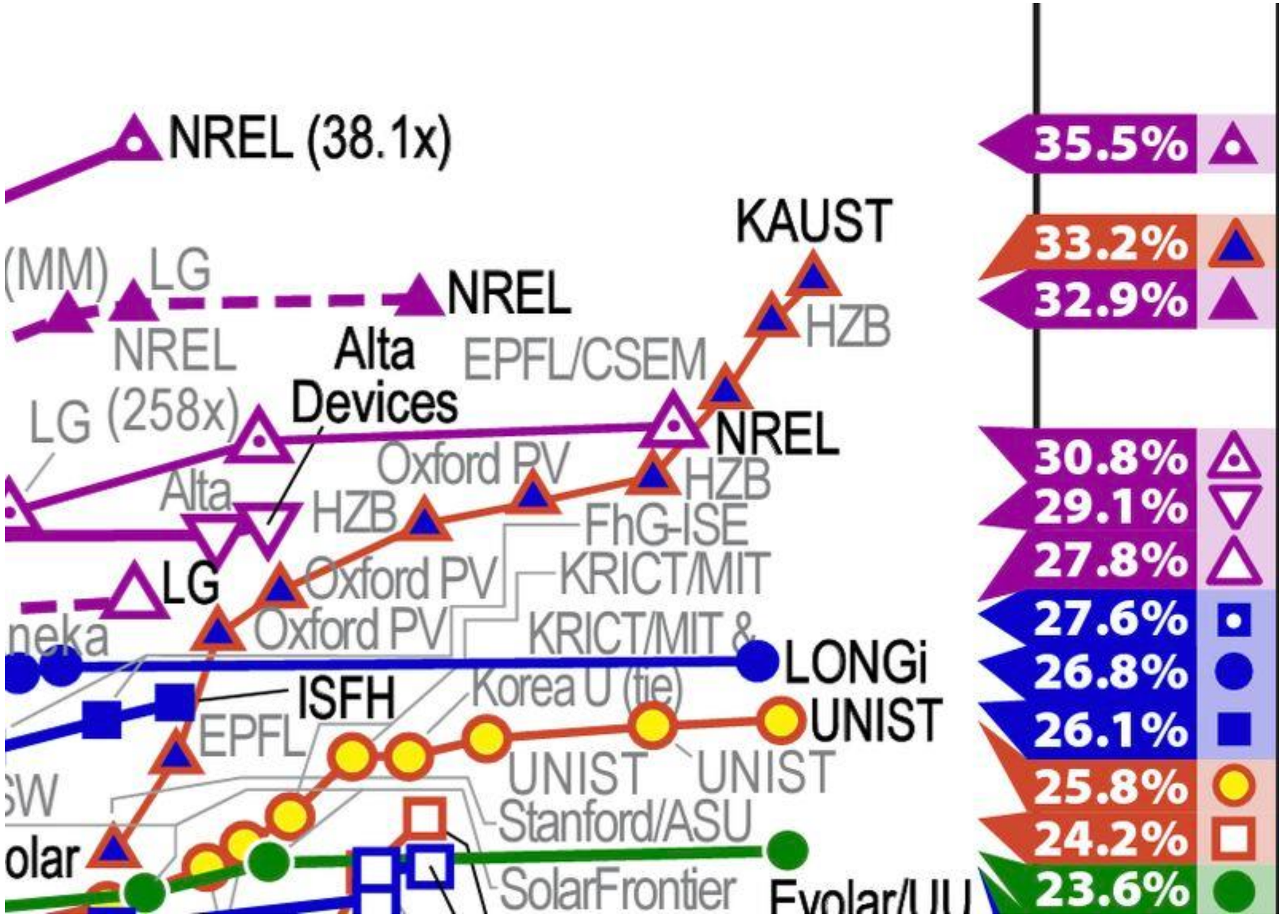
- ~%5 of the PV market is covered by thin-film solar cells *



* Fraunhofer ISE: Photovoltaics Report, updated: 21 February 2023

Interesting fact,2: Future of thin-film PV

- Perovskites are expected to change the equation soon!



Si/Perovskite tandem

Si only

- **Only affordable PV technology proven to surpass Si efficiency**
- **Si hitting physical limits**
- **Tandem production lines can be added to the existing Si lines**

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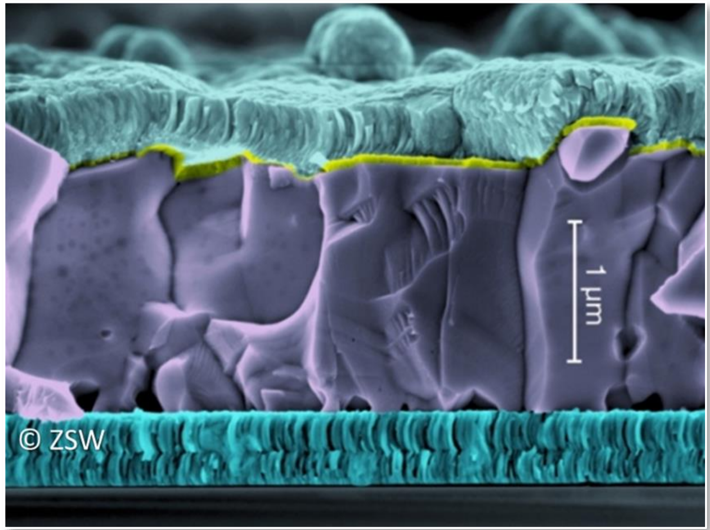
* Image credits: https://www.nrel.gov/pv/cell-efficiency.html

Interesting fact,2

Economic value of metrology: Example thin film solar cells (simplified)



[*]

[**]

Up to absorber:

≈38% of total cost → ≈23% of total cost

≈7.6 M€ / year

95% efficient

From absorber to flasher:

≈23% of total cost

≈4.6 M€ / year

100% efficient

1. Late detection → 380,000 €/year
   + 230,000 €/year loss
2. Early detection → 380,000 €/year loss ⇨ +Investment cost = 100,000 €

230% return of investment after one year

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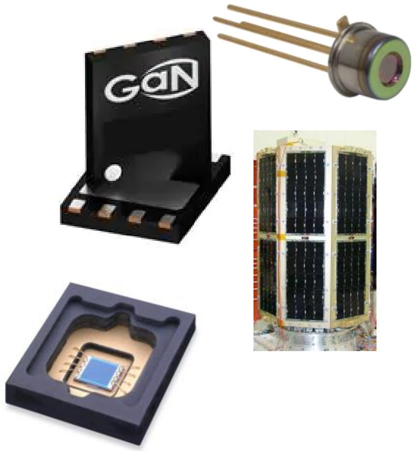
* Zentrum für Sonnenenergie- und Wasserstoff-Forschung (ZSW), www.zsw-bw.de
** K. A. W. Horowitz et al., NREL/PR-6A20-64507, 2015

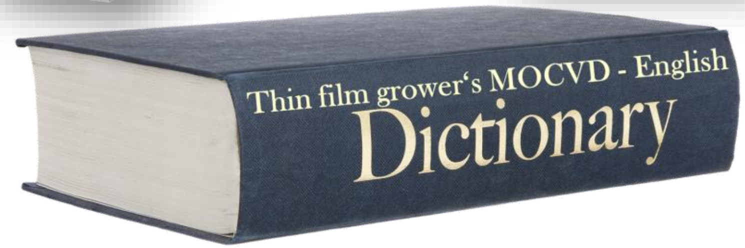
On the road to higher performance, higher yield and lower cost …



System → Device → Material → Process → Production tool

Requirements →

← Understanding



→ Metrology helps you to understand – metrology can be your dictionary!

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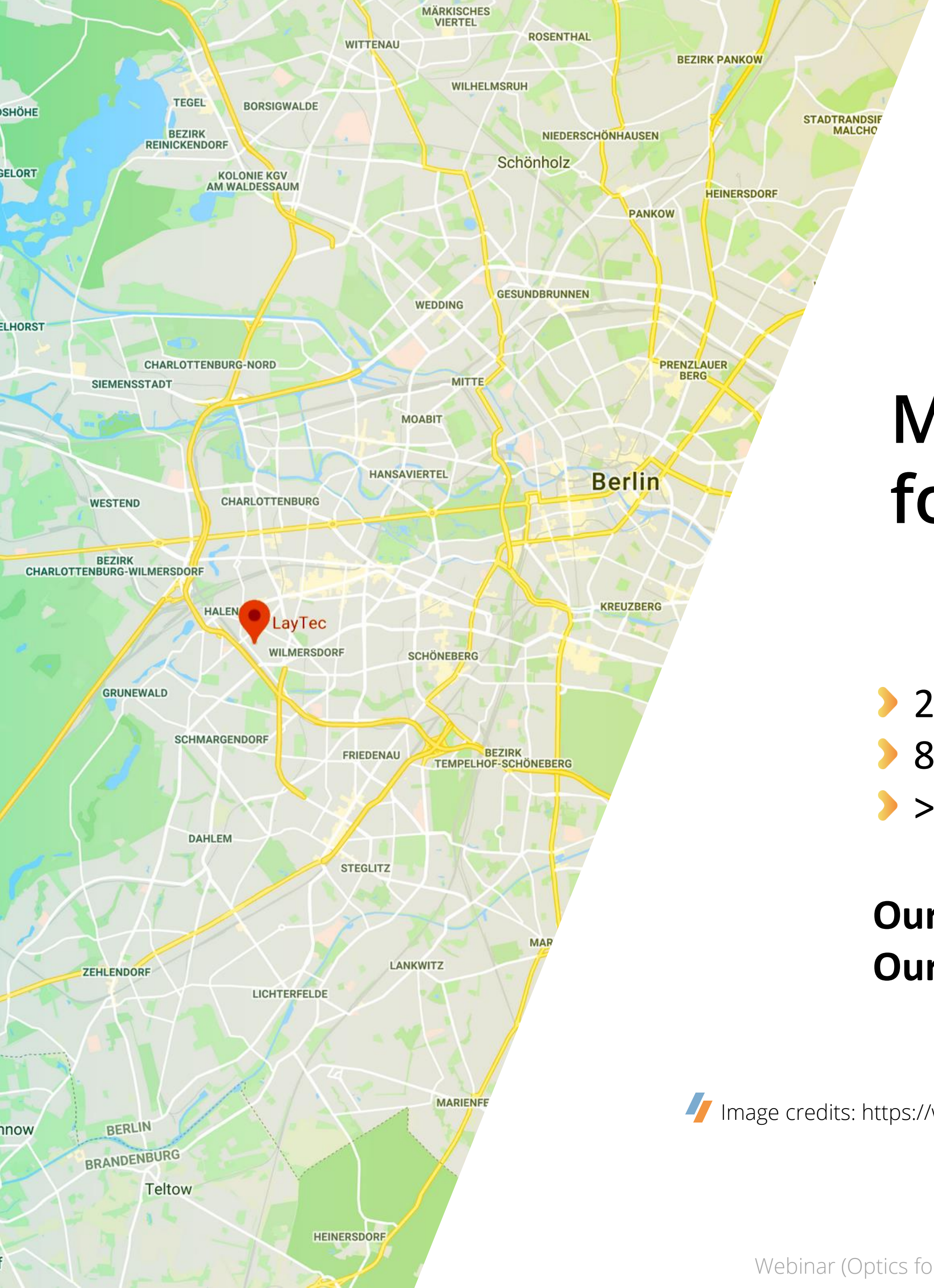
Outline



Metrology company founded 1999 in Berlin

- 24 years old
- 85 employees
- >3500 systems sold
- Spin-off 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

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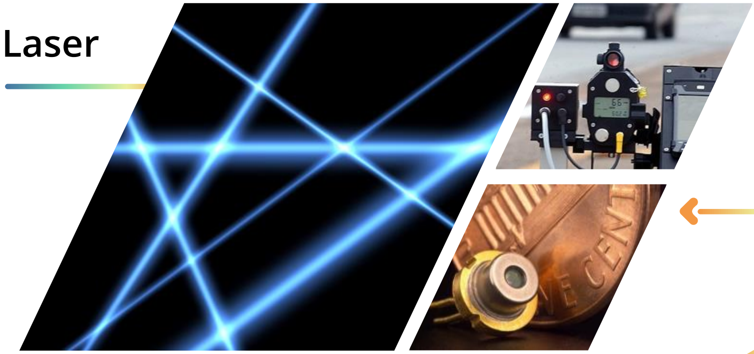
Integrated metrology for various industries and markets

Laser



LED

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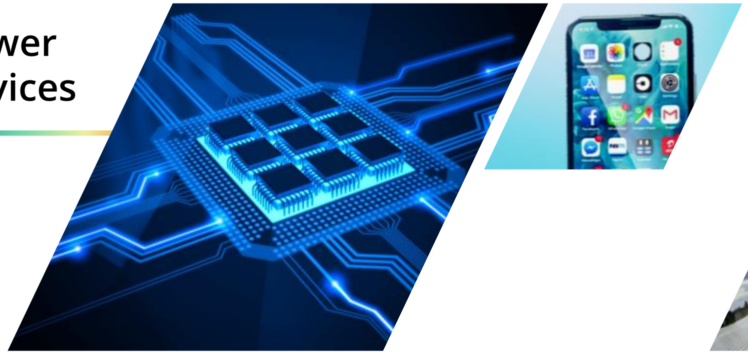
Functional glass

Power devices



Photovoltaics

Image credits: see last slide

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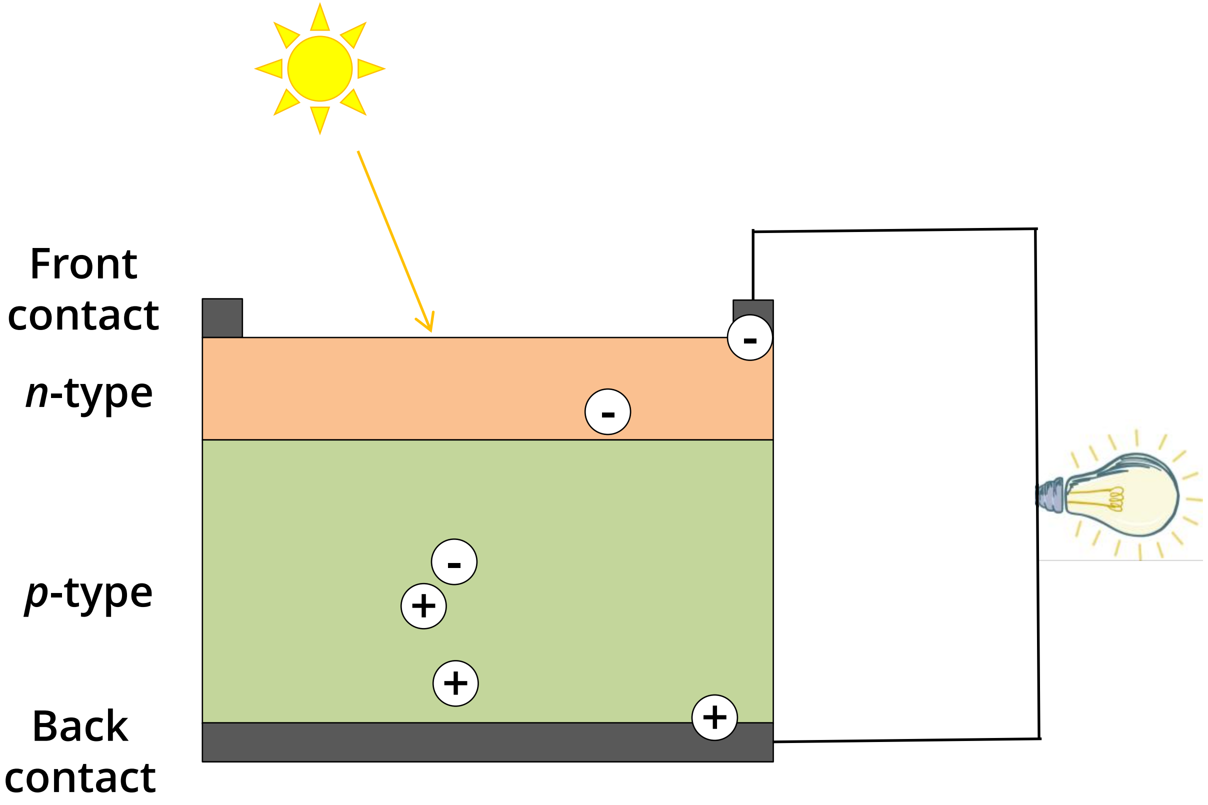
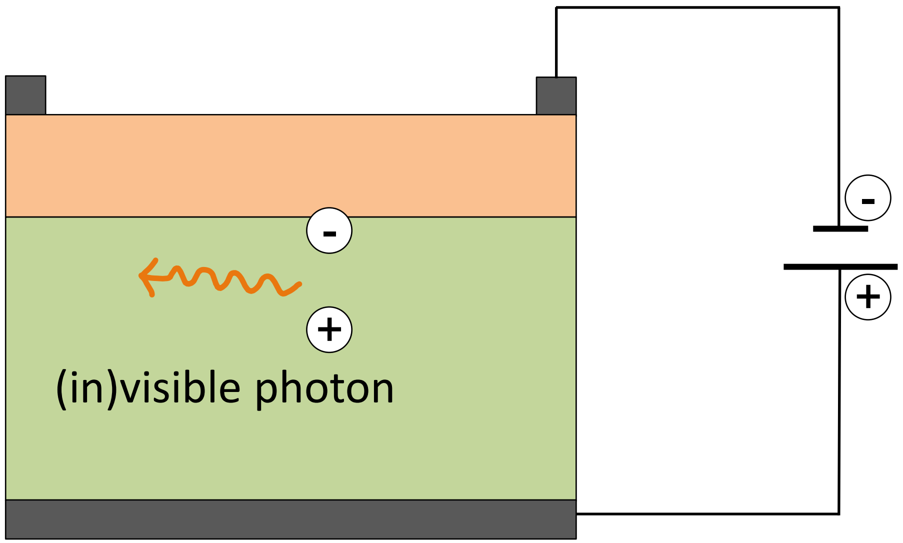
Light ⇔ Electricity in simple words



Solar cells



LEDs

Light ⇔ Electricity in simple words

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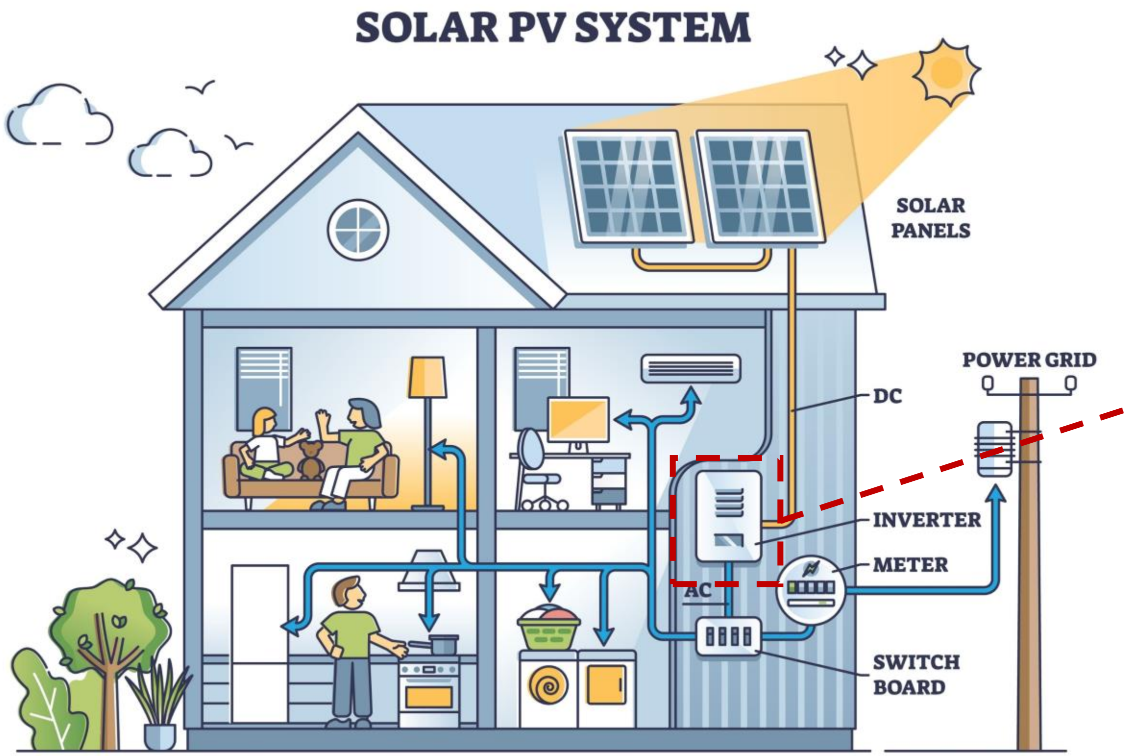

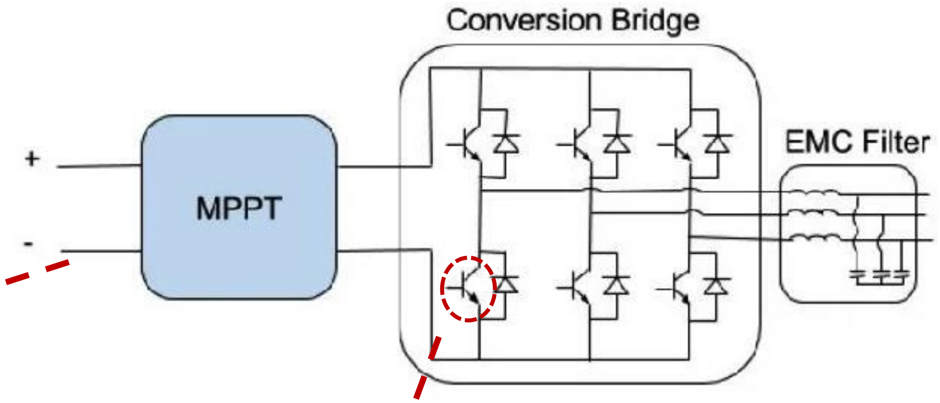

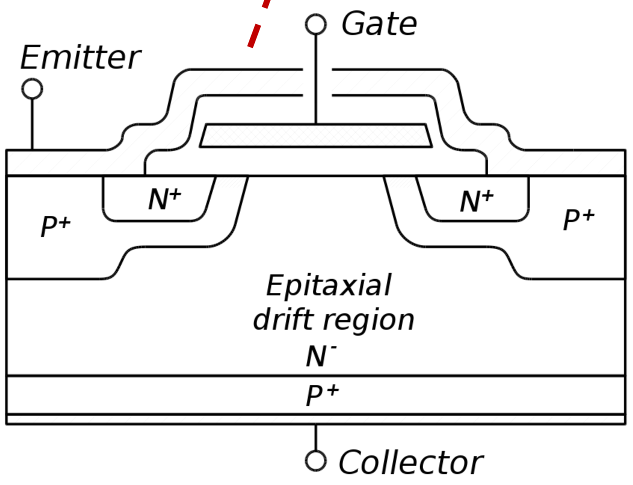

Insulated gate bipolar transistors (IGBT)

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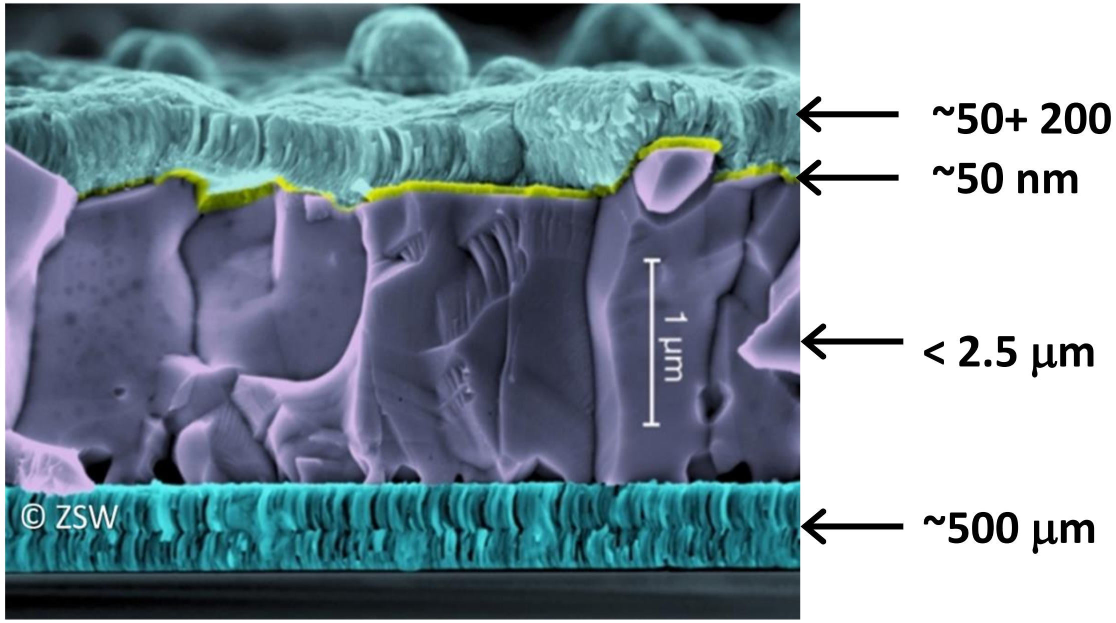
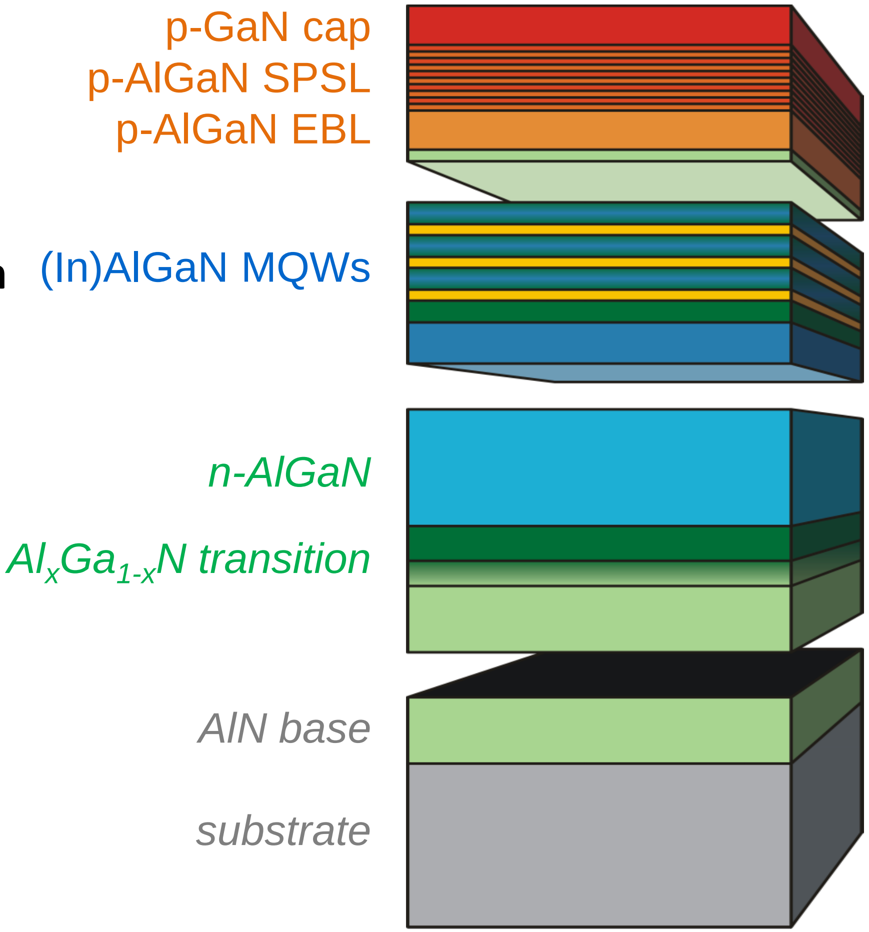
* https://eepower.com/technical-articles/an-introduction-to-inverters-for-photovoltaic-pv-applications/#
** Wikipedia: https://en.wikipedia.org/wiki/Insulated-gate_bipolar_transistor

What needs to be taken care of…

CIGS solar cell [*]



Deep UV LED[**]



- Composition
- Temperature
- Curvature and strain
- Surface roughness

* Zentrum für Sonnenenergie- und Wasserstoff-Forschung (ZSW), www.zsw-bw.de
** Kneissl, M et al.. Nat. Photonics 13, 233–244 (2019). https://doi.org/10.1038/s41566-019-0359-9

Outline

Motivation

Scope, financial aspects

Who are we?

History, markets, approach

Light <-> Electricity

LEDs, Solar cells and transistors

Reflectometry, deflectometry and pyrometry

Case studies

Conclusions

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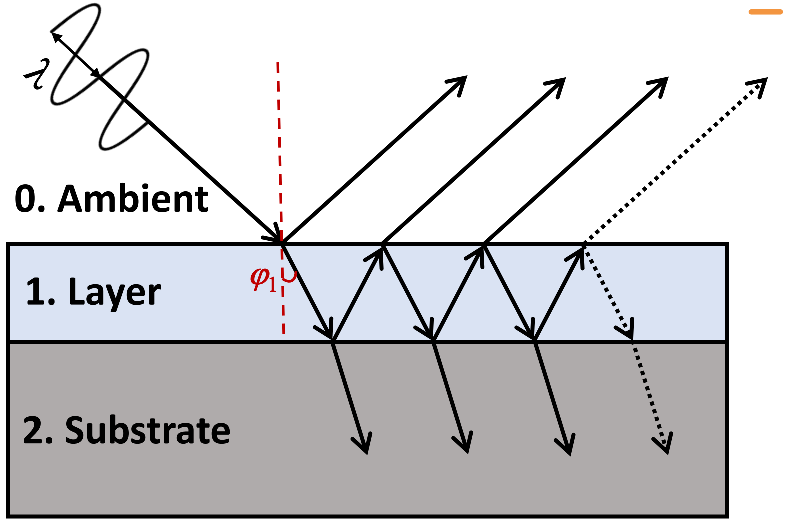
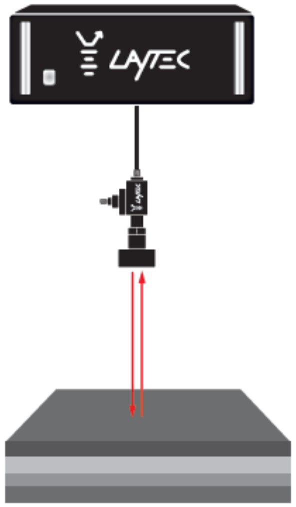
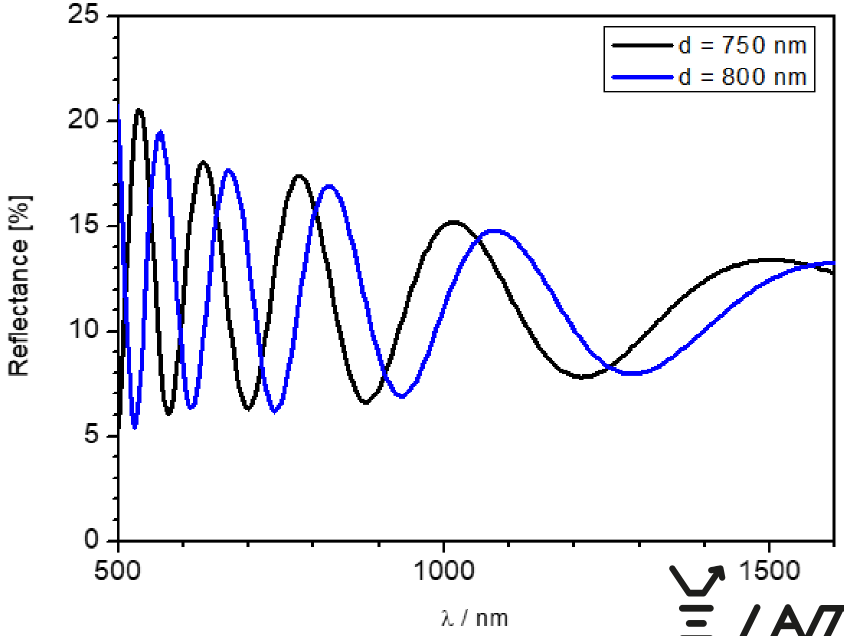
Reflectometry

- **Interference is:**
  - Constructive at $2nd_1 = m\lambda$
  - Destructive at $2nd_1 = (m+1/2)\lambda$
- $r = \dfrac{r_{01} + r_{12}e^{-2i\beta}}{1 - r_{10}r_{12}e^{-2i\beta}}$ **where** $\beta = 2\pi \dfrac{d_1}{\lambda}\widehat{n_1}\, cos\varphi_1$
  - **Reflectance,** $R = |r|^2$
- **Light source**
  - White light
  - Monochromatic
- **Fabry-Perot oscillations**
  - Spectral
  - Temporal (growth oscillations)



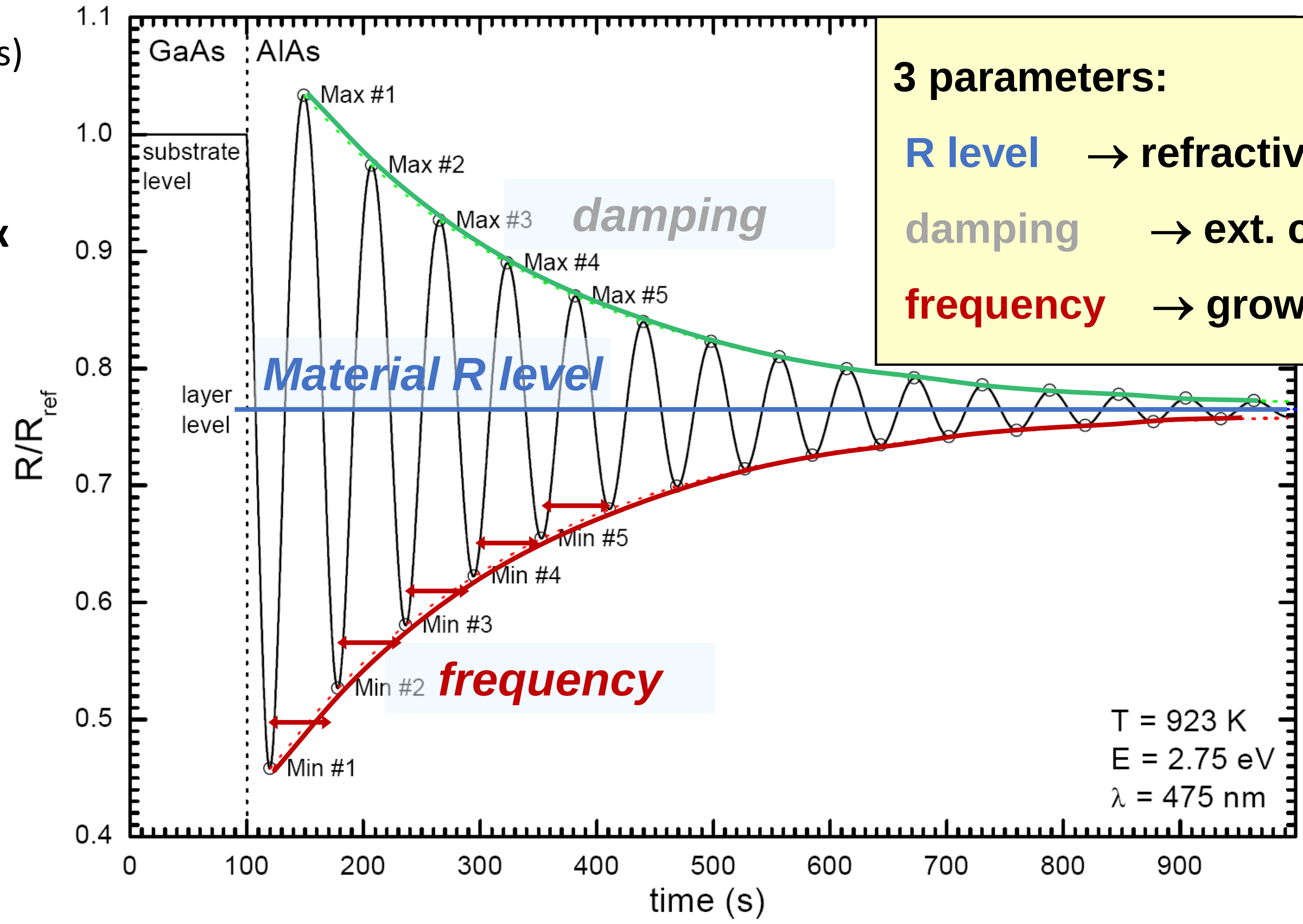




Reflectometry

- **Fabry-Perot oscillations**
  - Temporal (growth oscillations)

→ Information on film thickness (growth rate) and refractive index



3 parameters:

R level → **refractive index *n&k***

damping → **ext. coefficient *k***

frequency → **growth rate *r***

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- **Motivation**
  Scope, financial aspects
- **Who are we?**
  History, markets, approach
- **Light ←→ Electricity**
  LEDs, Solar cells and transistors
- **Reflectometry, deflectometry and pyrometry**
- **Case studies**
- **Conclusions**

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Deflectometry: curvature basics

concave
upwards
positive curvature

convex
downwards
negative curvature

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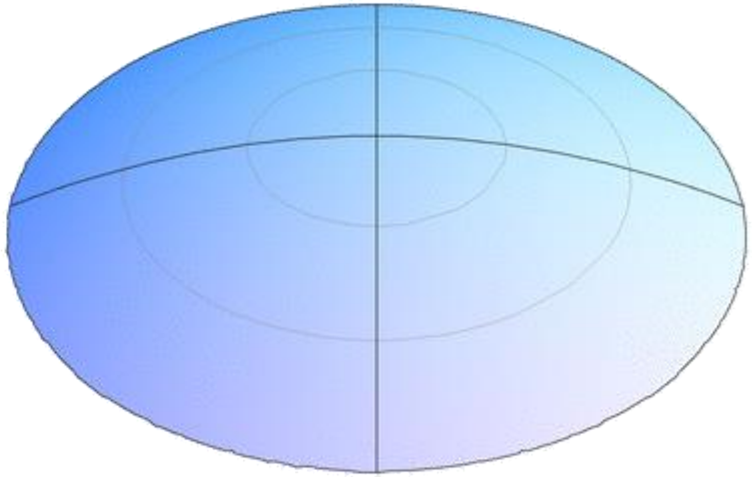
Deflectometry: curvature basics



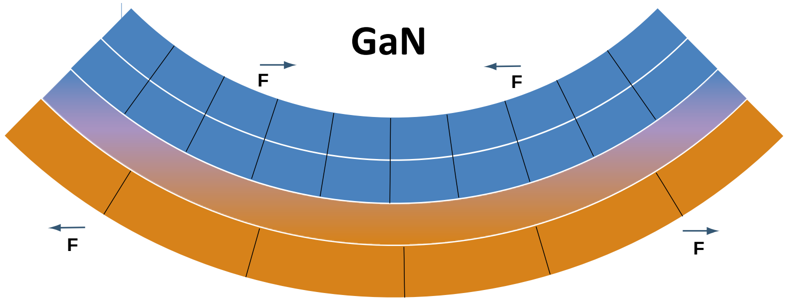
Concave

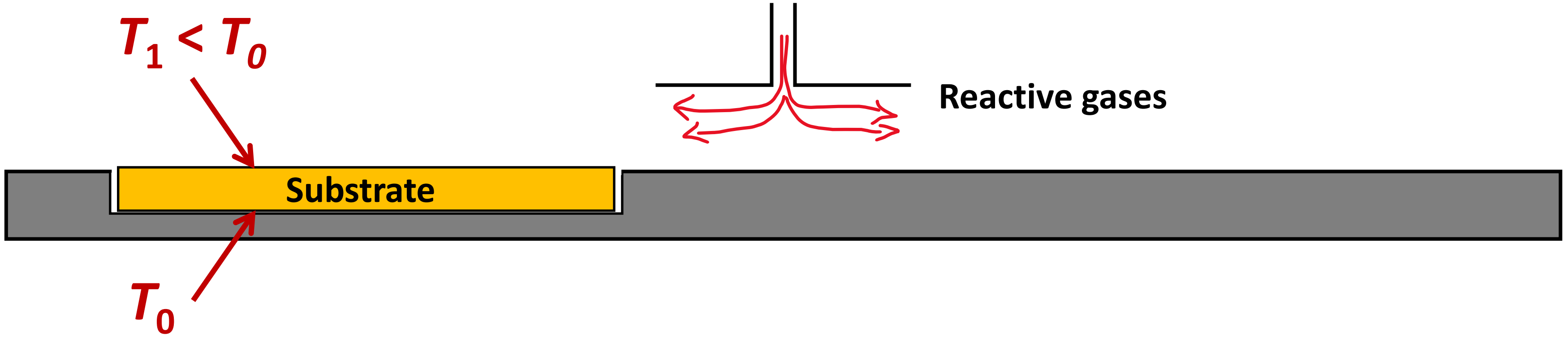
Flat

Convex

Why does it happen?

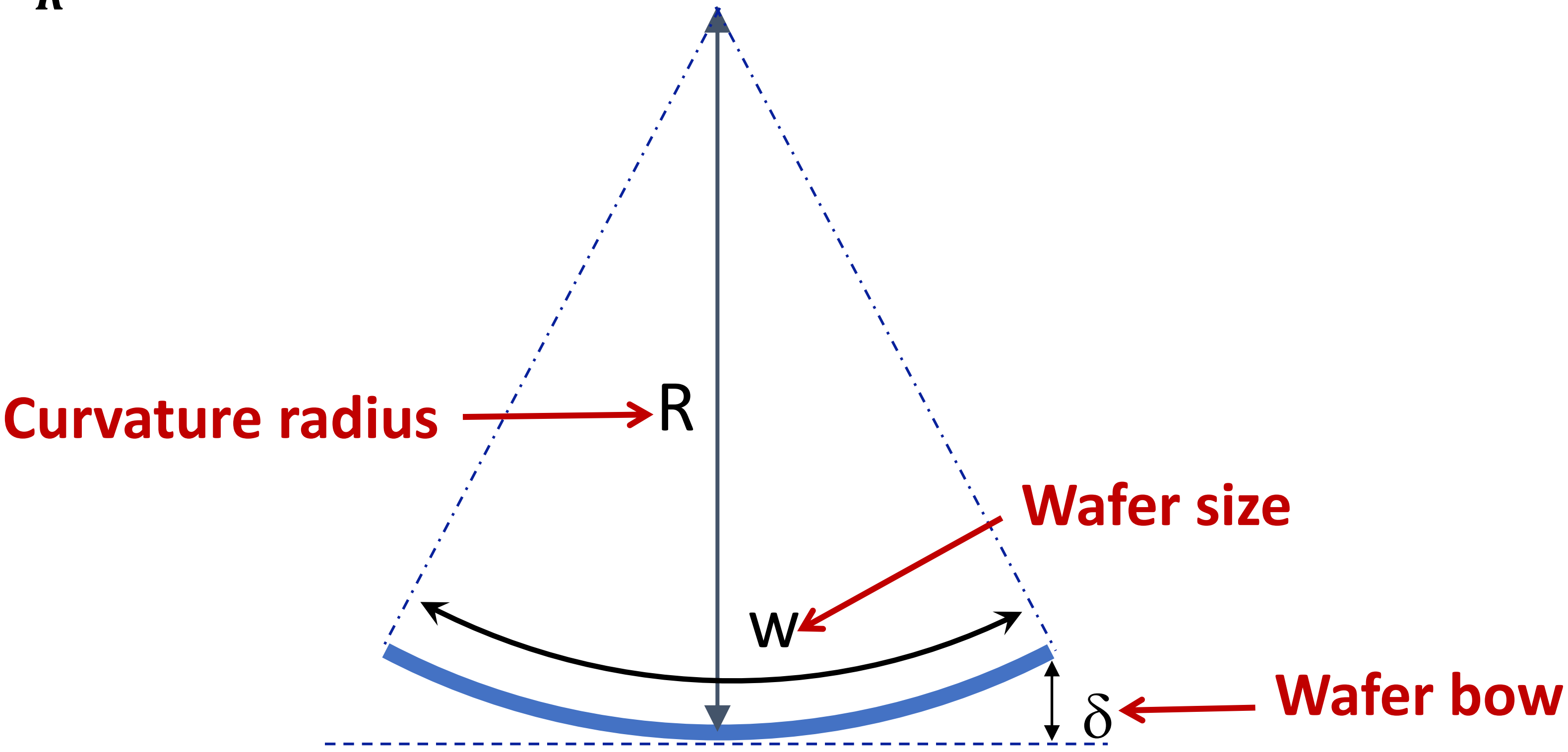
- Uneven temperature
- Lattice mismatch
- Thermal expansion mismatch





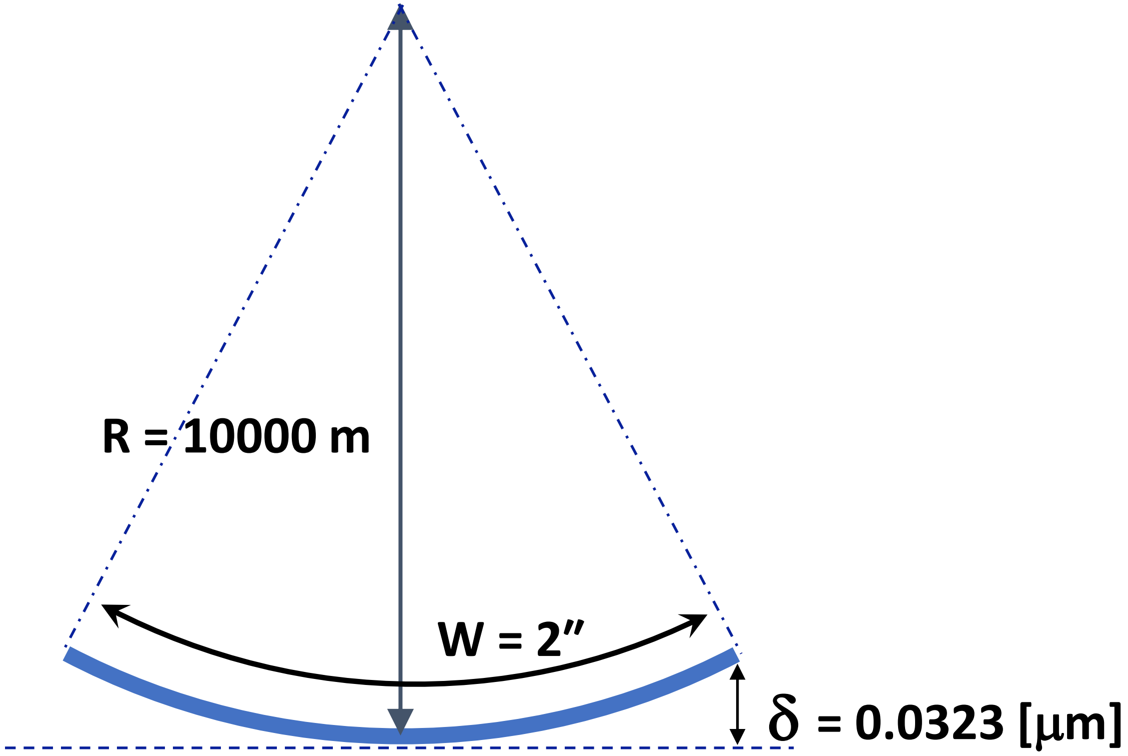
Curvature parameters and implications

- **Curvature** $k = \frac{1}{R}$



Curvature parameters and implications

- **Curvature k = 0.1 [km^{-1}]**



Curvature parameters and implications

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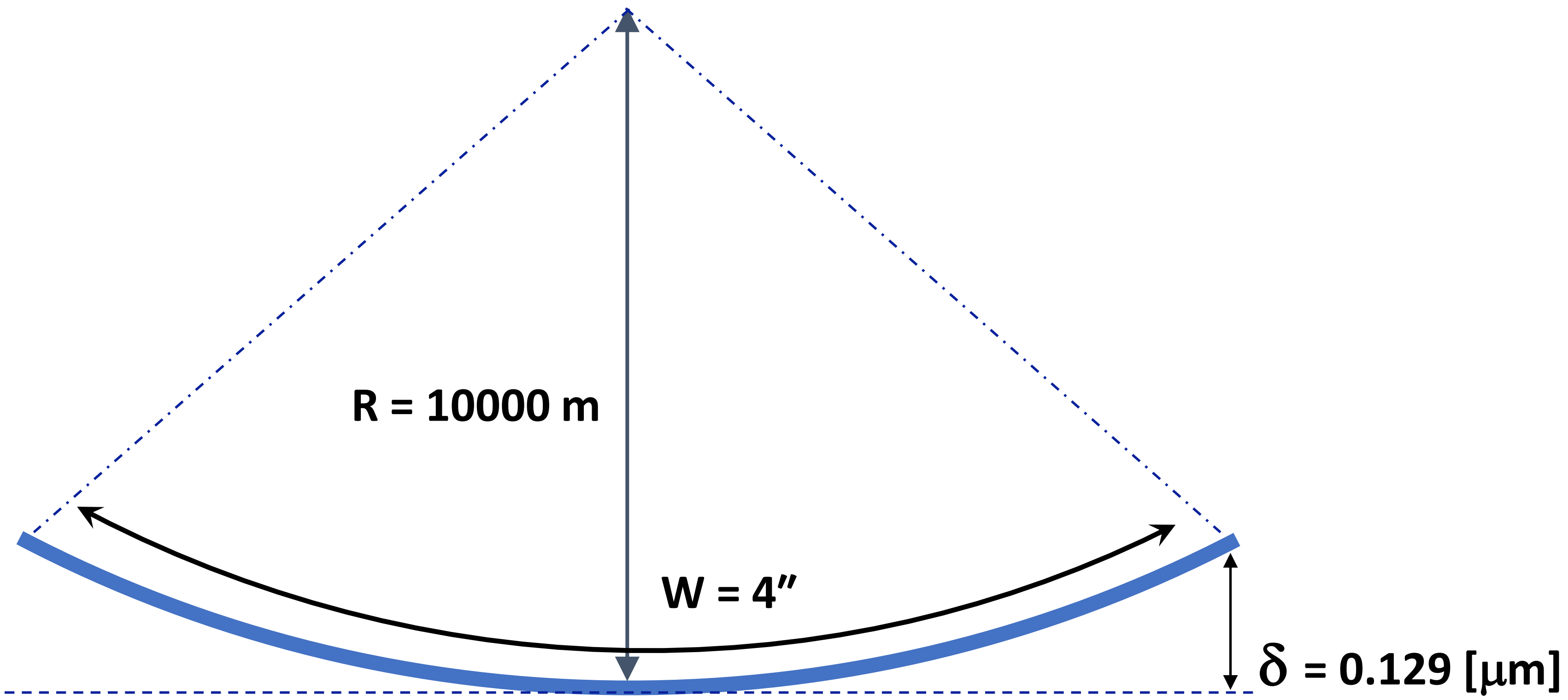
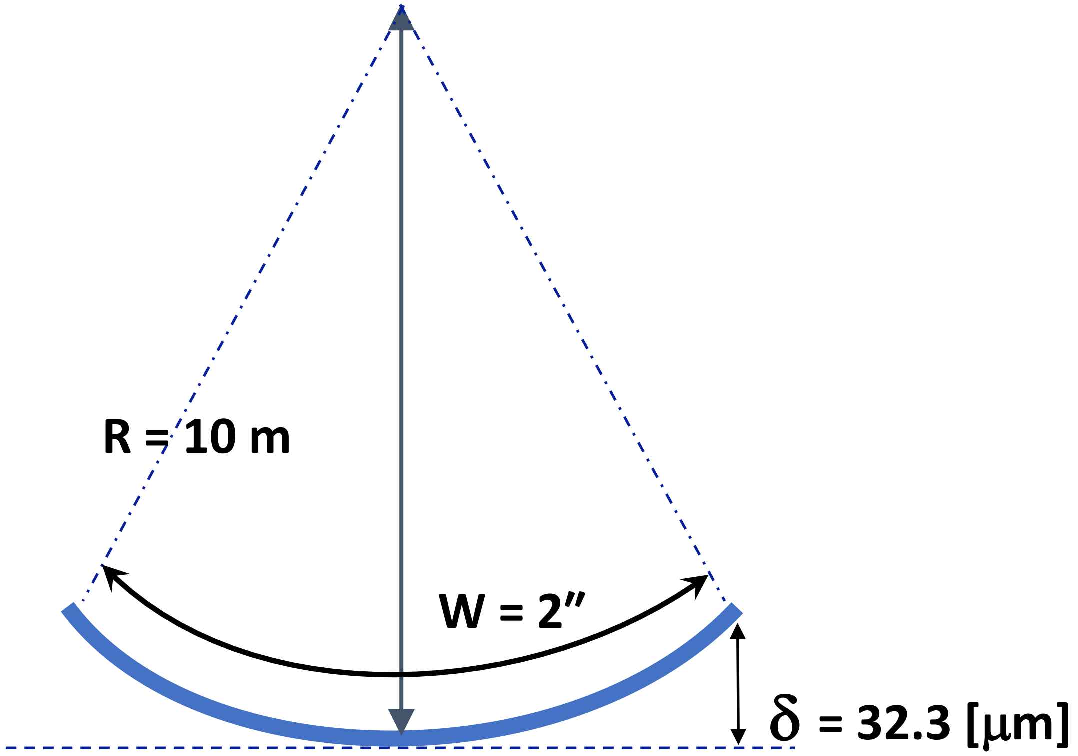


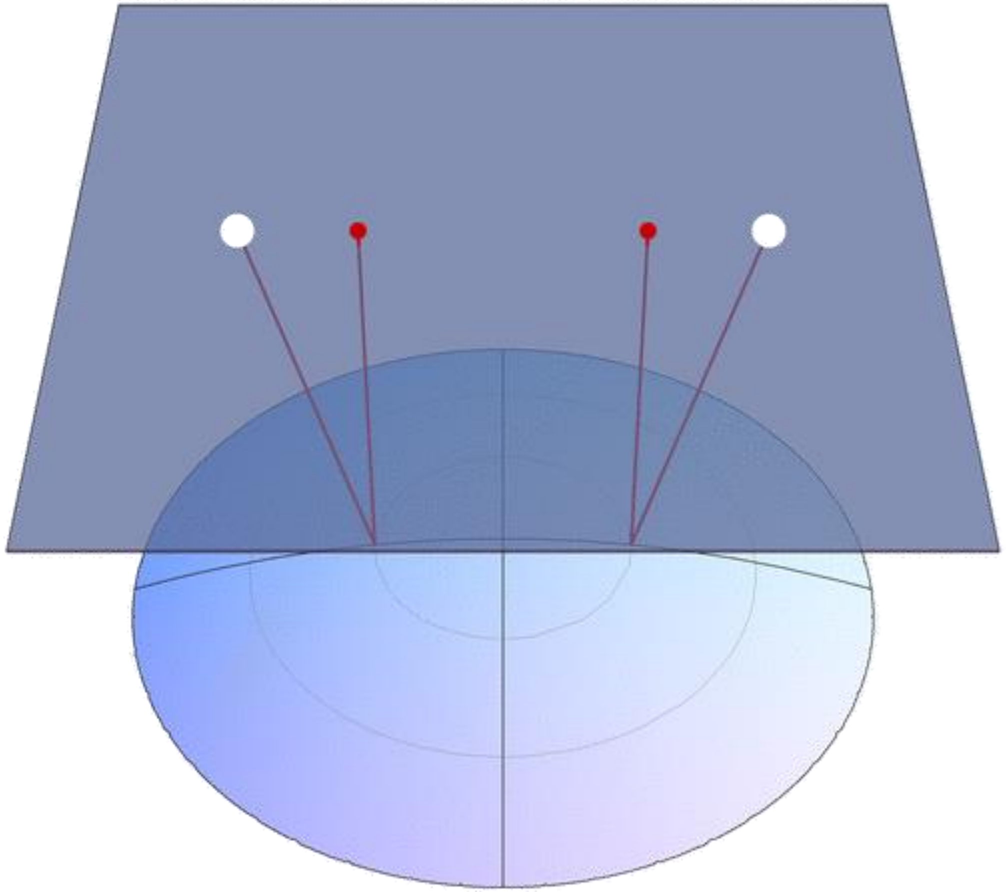
Curvature parameters and implications

- **Curvature k = 100 [km^{-1}]**
- **Why does it matter?**
  - **Temperature uniformity → performance uniformity**
  - **Avoid cracking**
  - **Avoid complications further down the chain, e.g in lithography**



Deflectometry

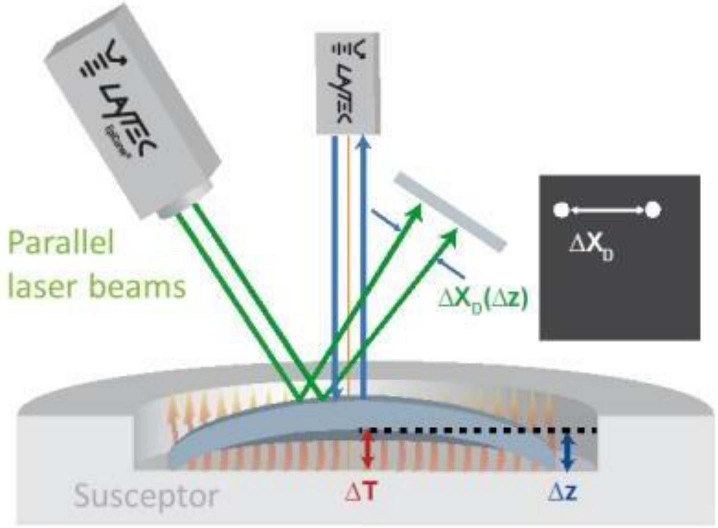
- Incident beam
- Reflected beam



Concave

Flat

Convex



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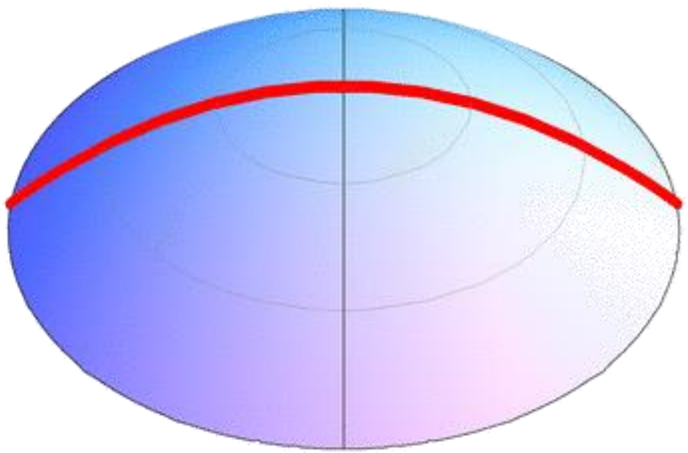
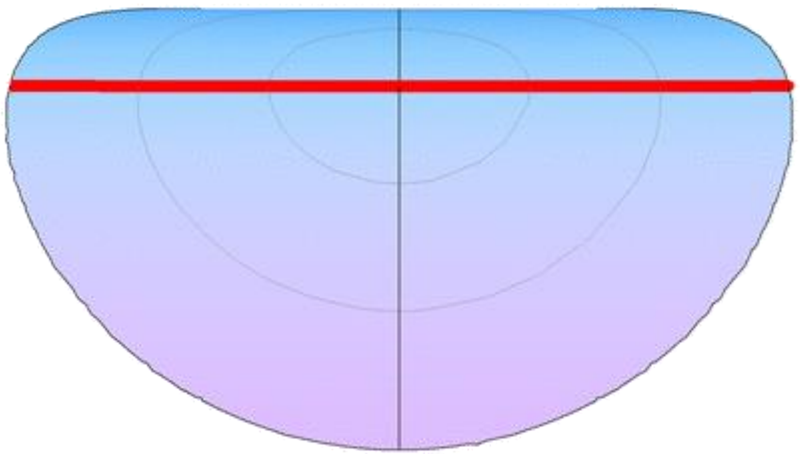
Deflectometry: Aspherical bowing

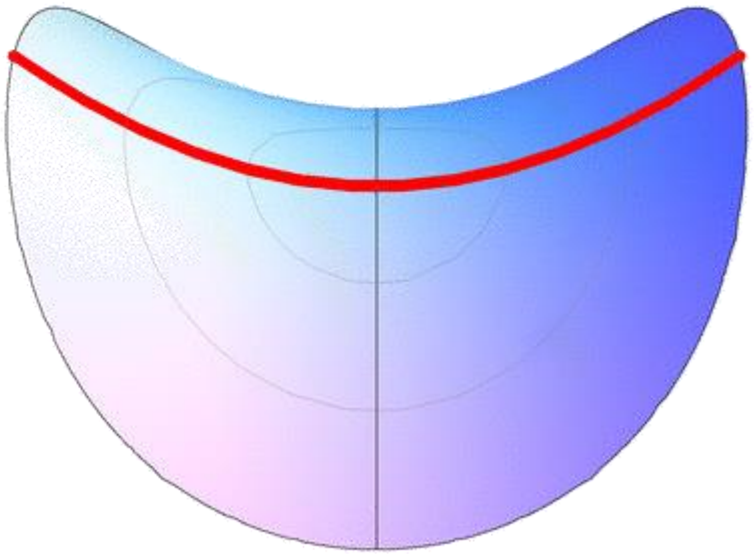
Spherical



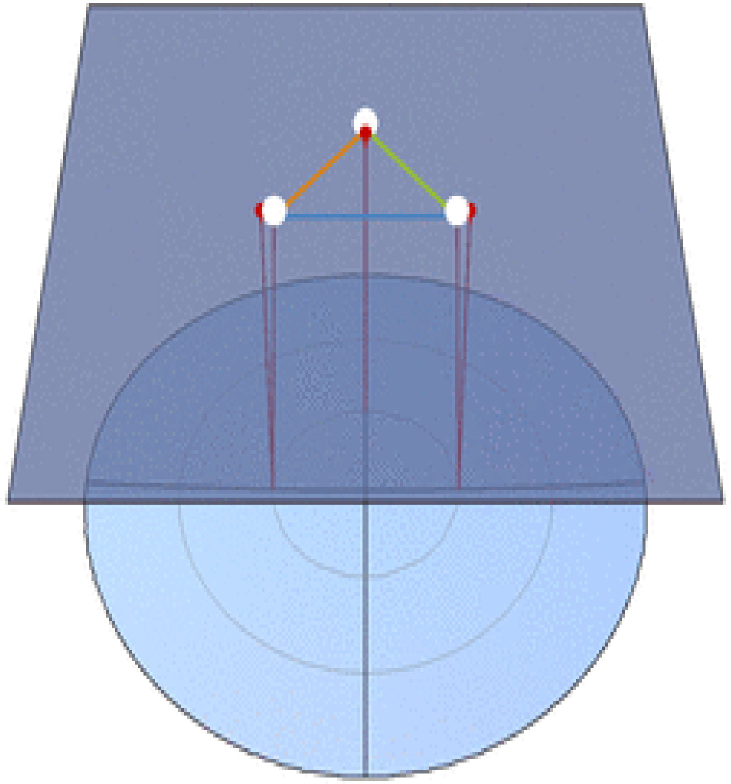
Parabolic



Hyperbolic



Solution: 3-point measurement



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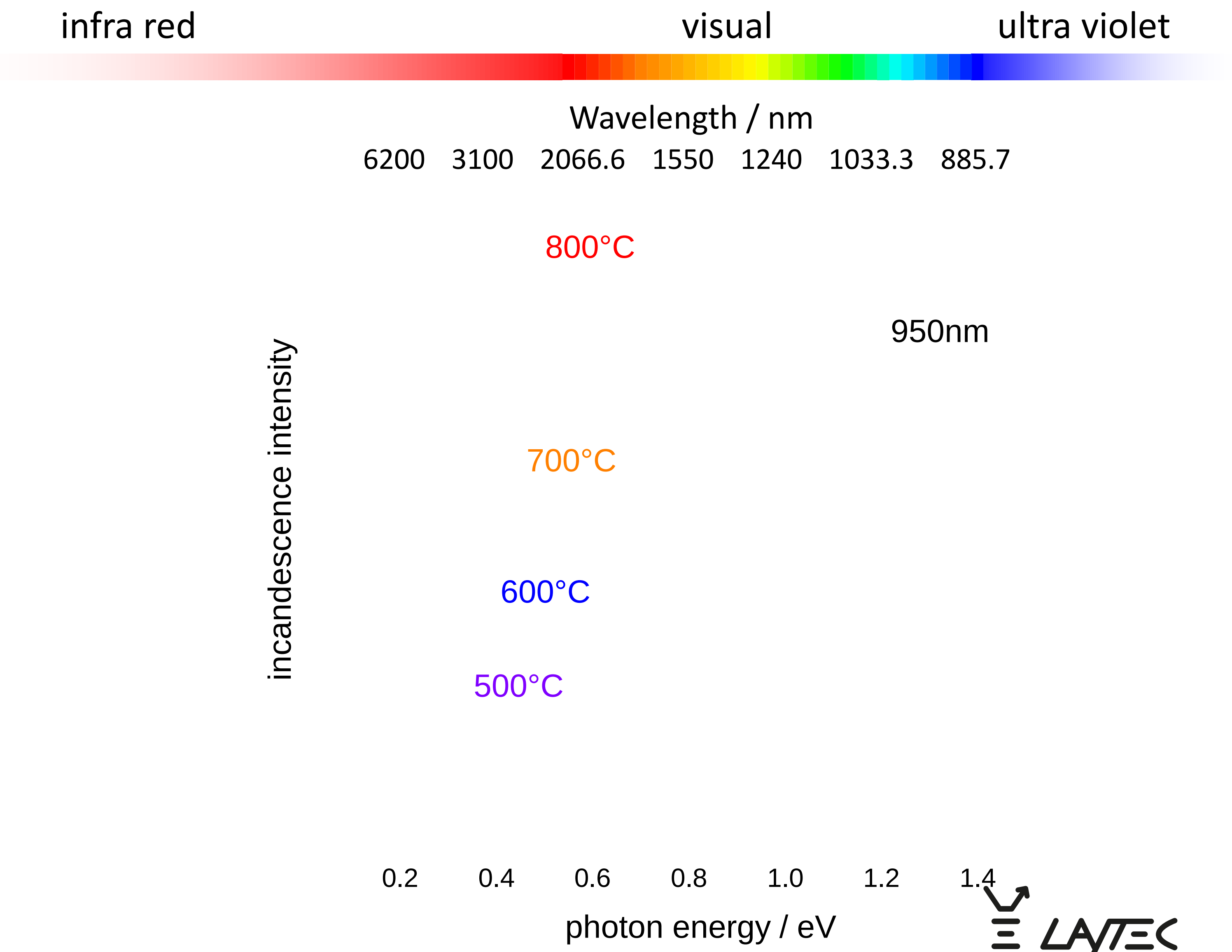
Pyrometry: how does it work?

- Plank’s equation for black body*:



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

- Normal materials:

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

emissivity

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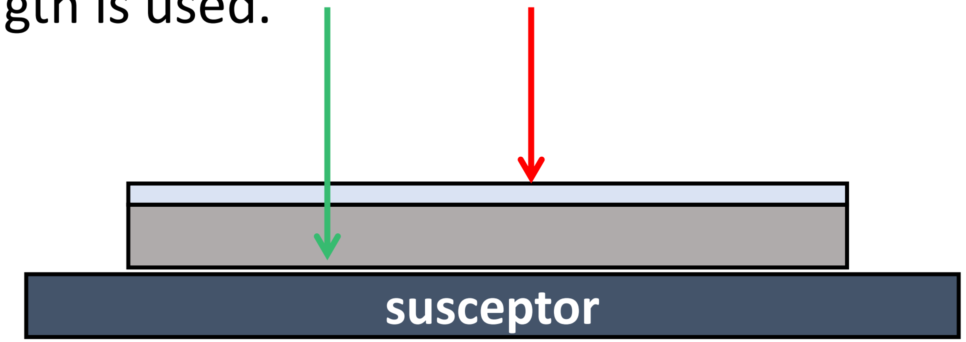
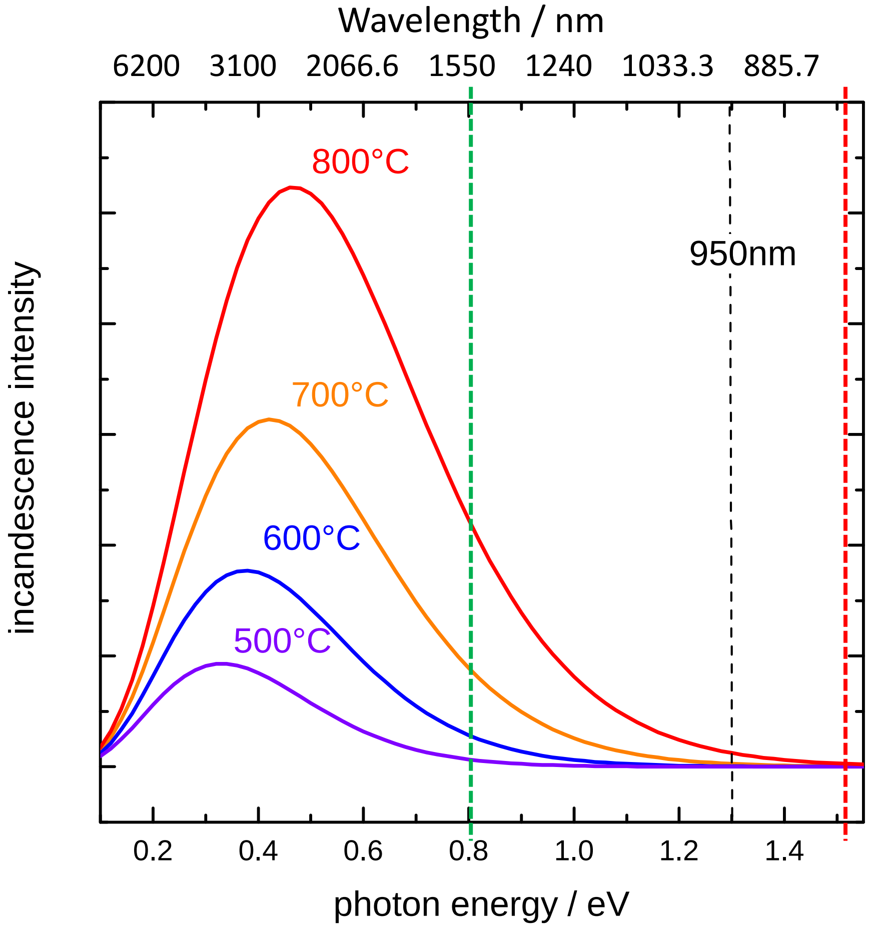
* Planck, Max. "The theory of heat radiation." Entropie 144.190 (1900): 164.

Pyrometry: why 950 nm?

- Epitaxy deals with **surface** chemistry.
- Lower photon energies → transparency regime → susceptor temperature.
- Higher energies → not enough intensity
- 950 nm best choice for most applications
- For transparent substrates (SiC), even shorter wavelength is used.





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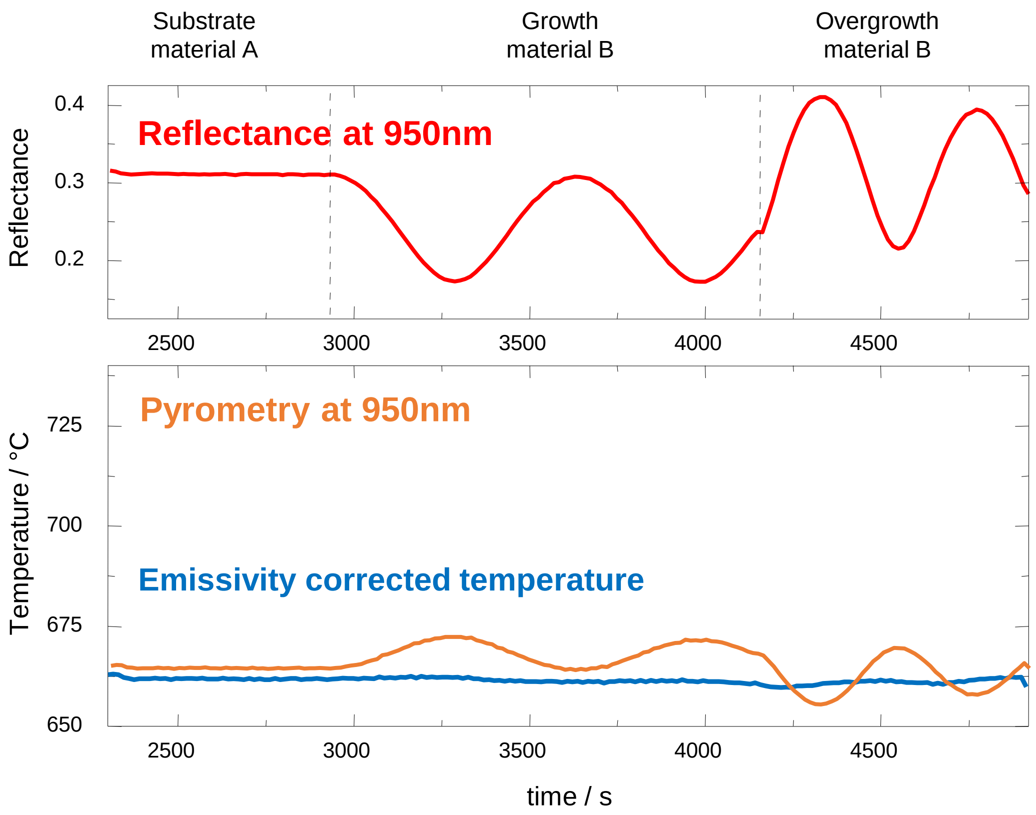
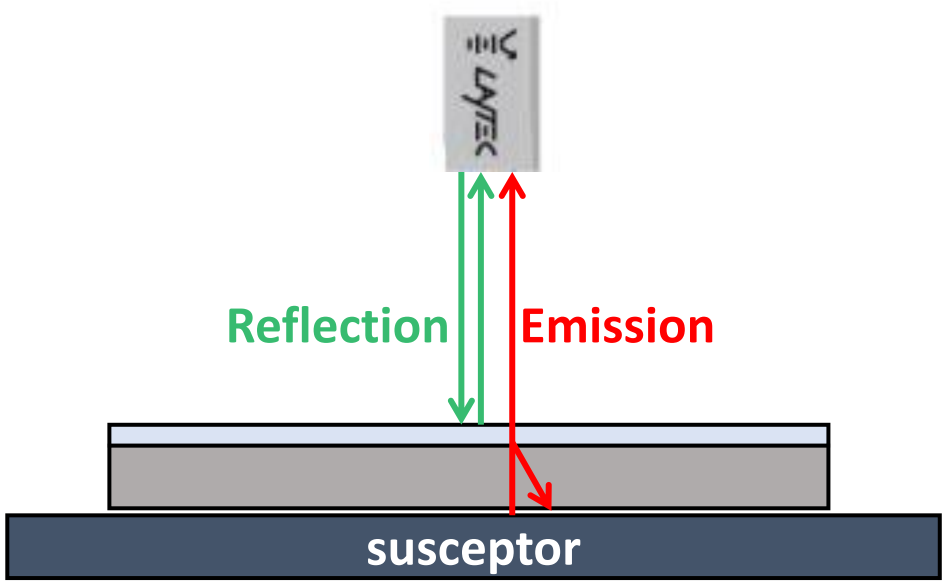
Pyrometry: emissivity correction

- Conservation of energy
  - $\alpha + r + t = 1$
  - Opaque semiconductor: $\alpha + r = 1$
- Kirchhoff's law: $\alpha(\lambda,T) = \varepsilon(\lambda,T) \rightarrow \varepsilon = 1\text{-}r$





Outline

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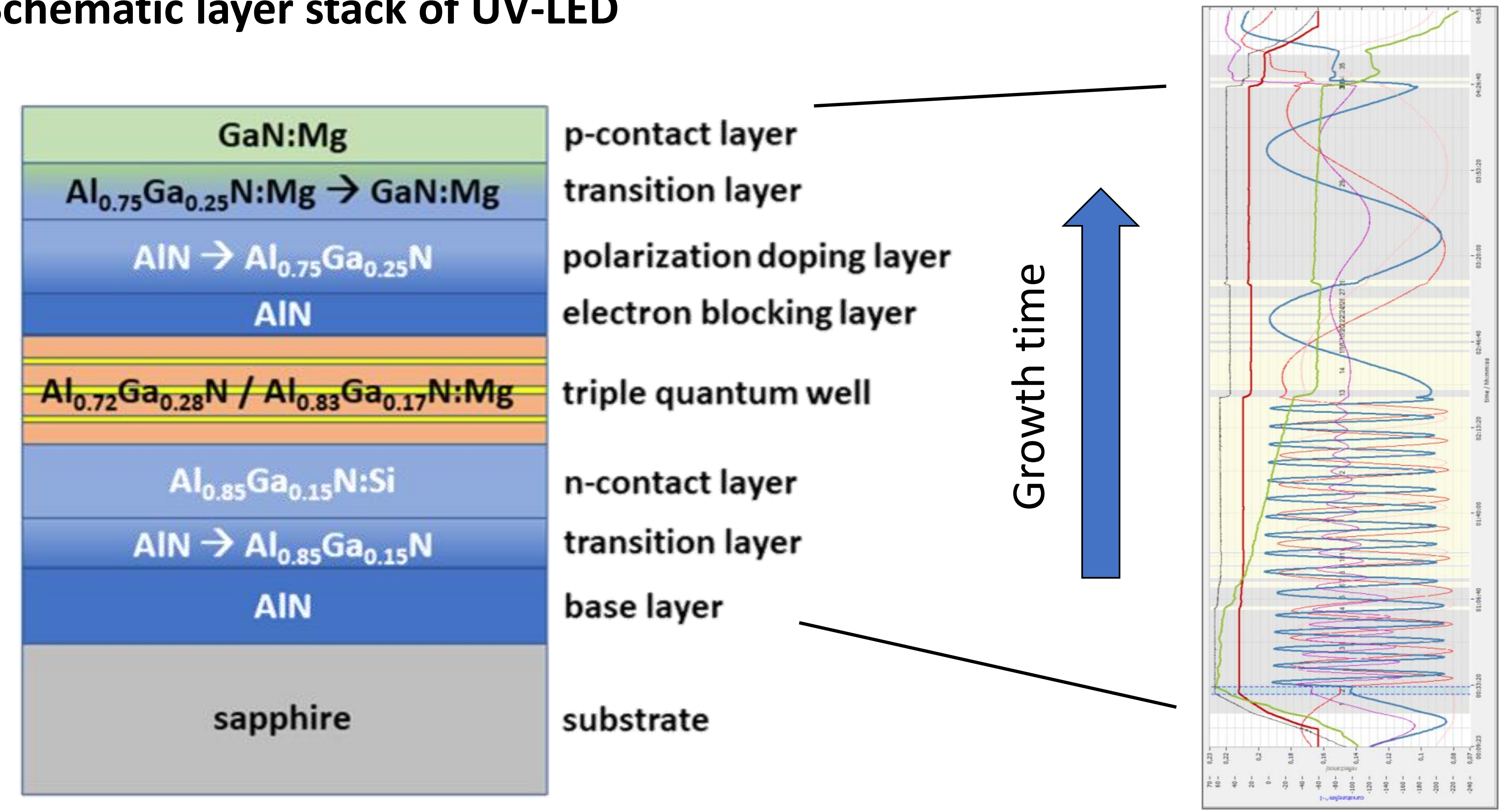
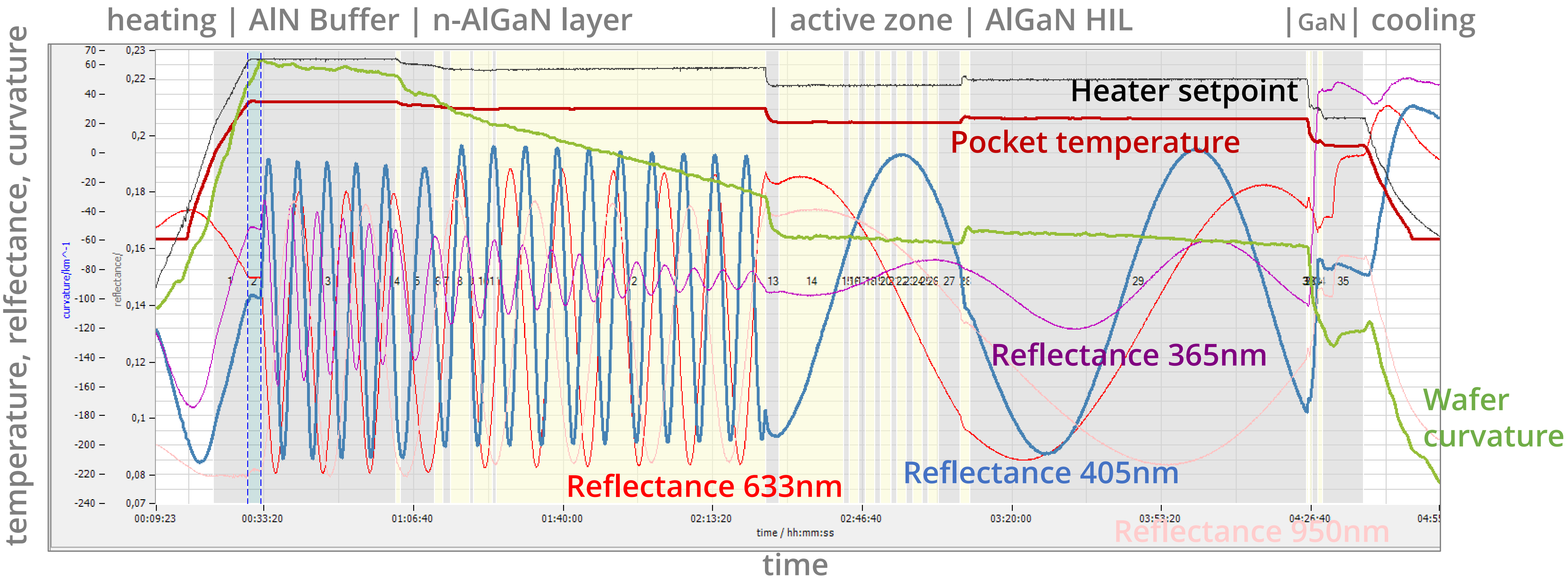
in-situ metrology for MOCVD of UV-LED structures

Schematic layer stack of UV-LED



In-situ data

In-situ data of 230 nm UV LED (wafer #1, center)



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

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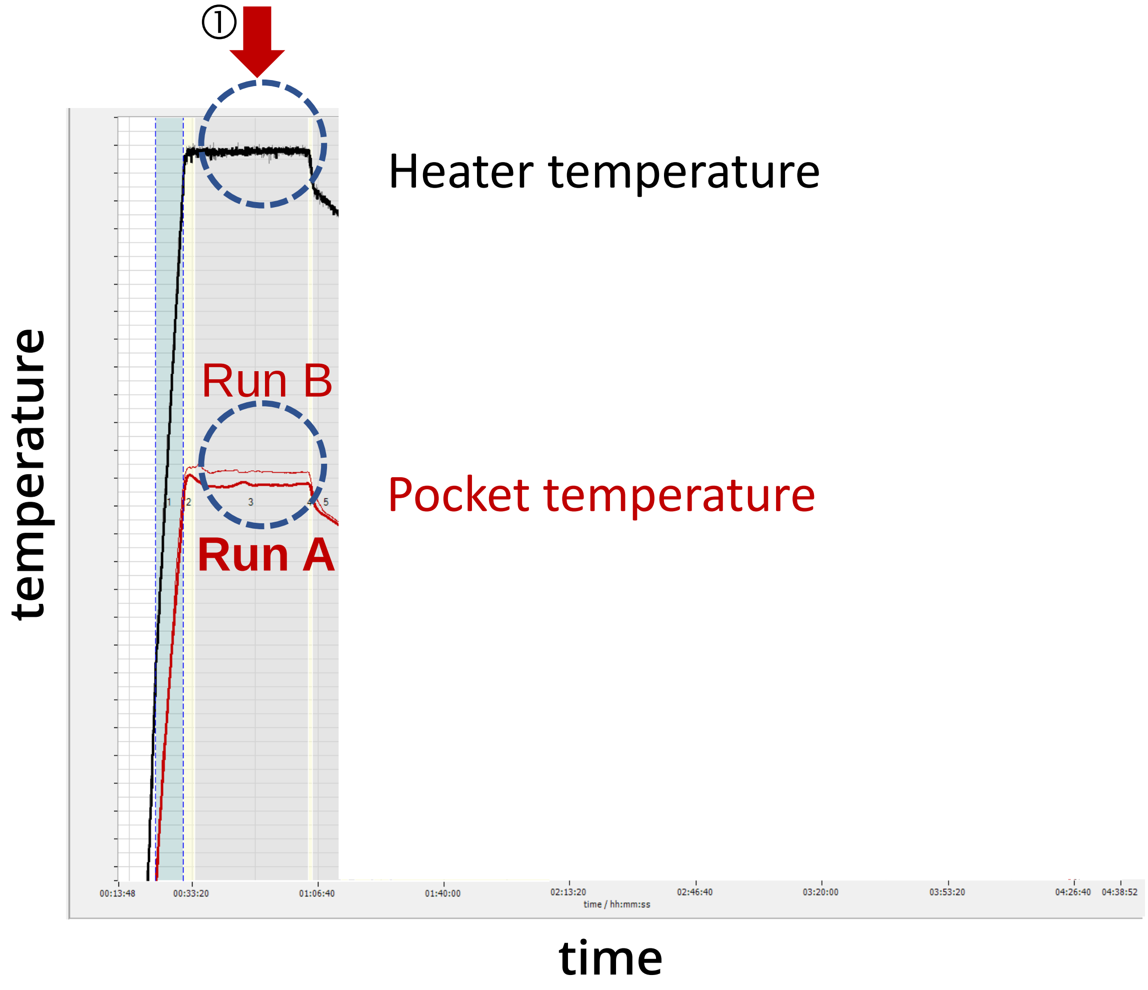
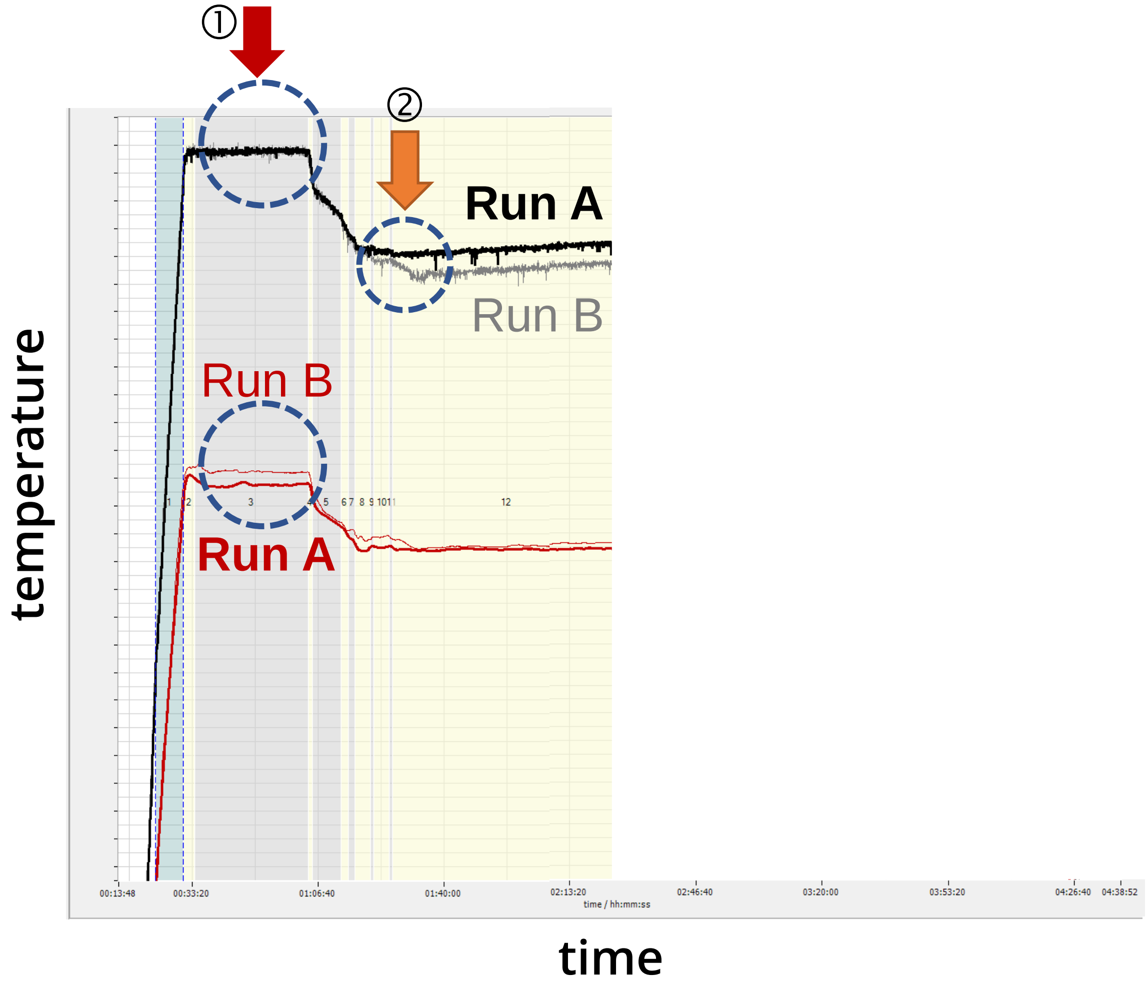
Feed-back control of pocket temperature



- **Run A and B (identical recipe):**
- **①: Same heater temperature**
- **Run B shows higher pocket temperature**

Feed-back control of pocket temperature



- **Run A and B (identical recipe):**
- **①: Same heater temperature**
- **Run B shows higher pocket temperature**
- **②: Correcting for difference: lowering process temperature in Run B**

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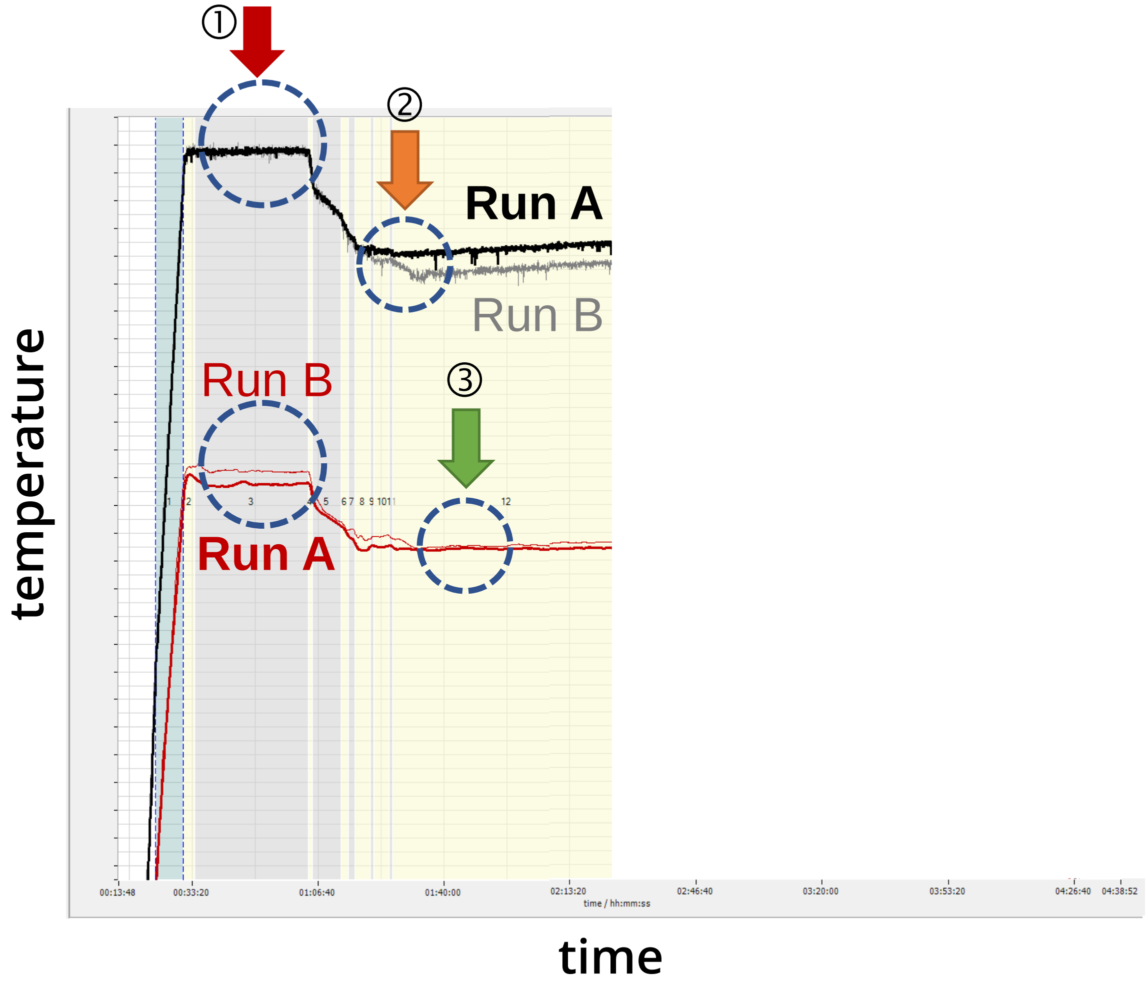
Feed-back control of pocket temperature

Leibniz
Ferdinand
Braun
Institut



- **Run A and B (identical recipe):**
- **①: Same heater temperature**
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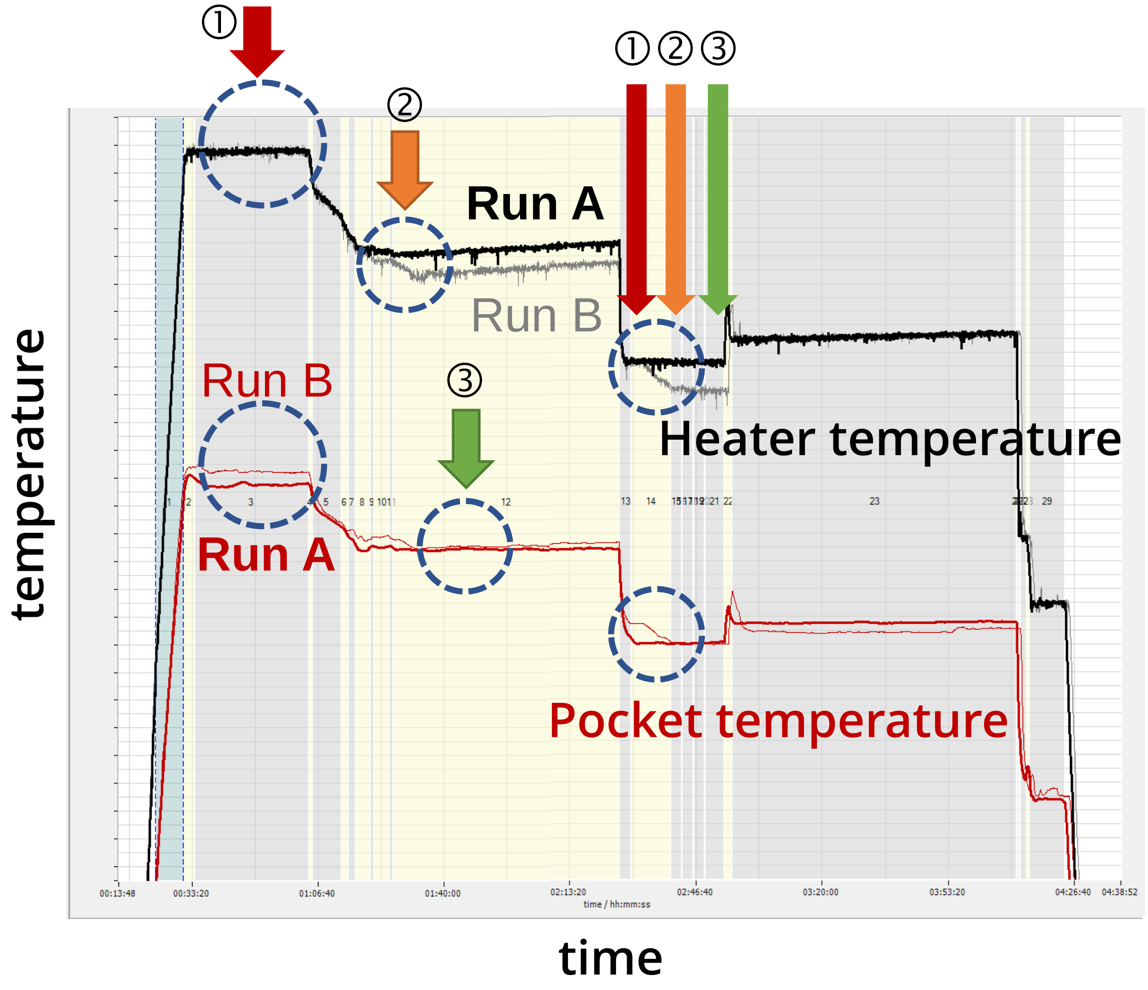
- **③: Same pocket temperature established as in Run A**

Feed-back control of pocket temperature



- Run A and B (identical recipe):
- ①: Same heater temperature
- Run B shows higher pocket temperature
- ②: Correcting for difference: lowering process temperature in Run B
- ③: Same pocket temperature established as in Run A
- Same effect in 2nd half of run

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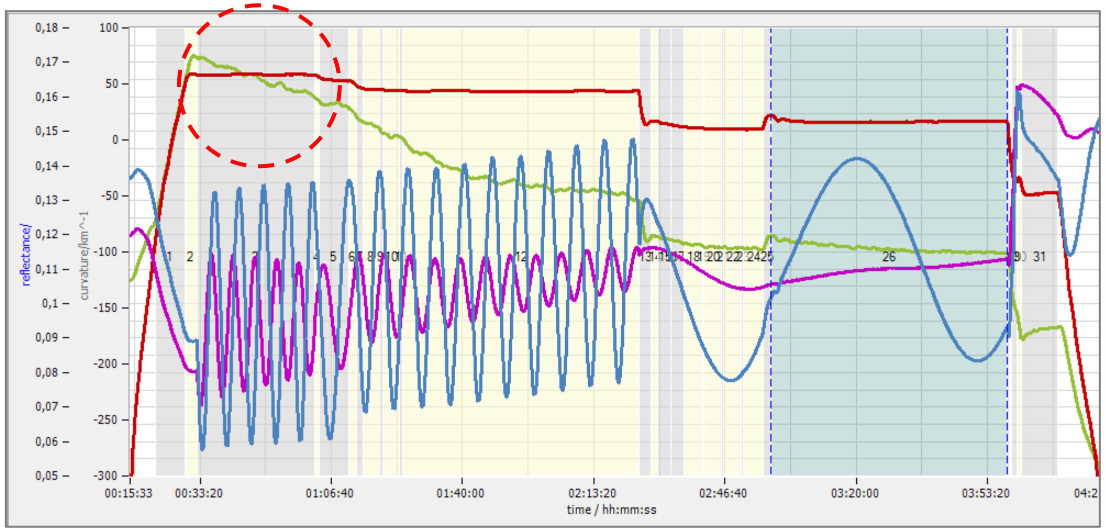
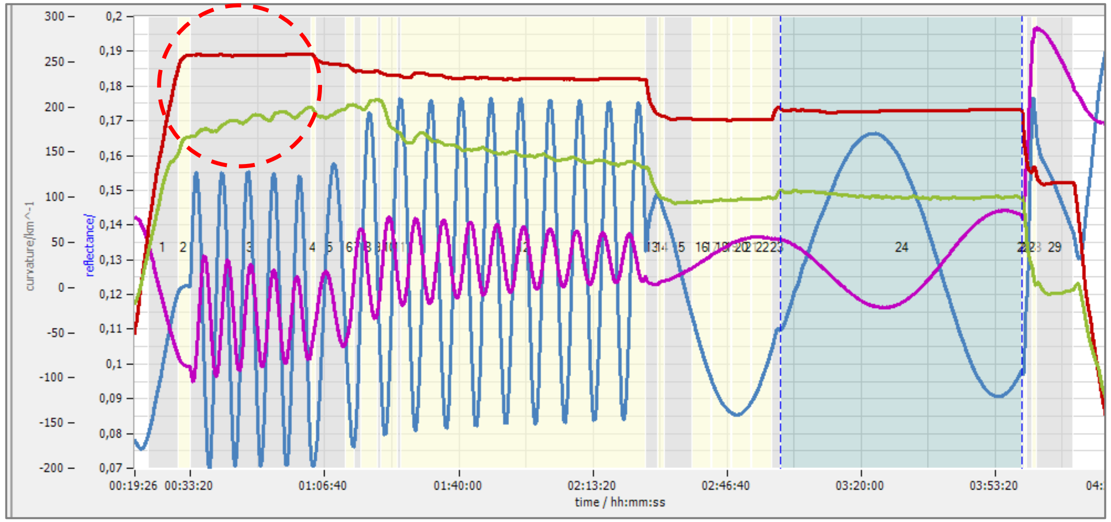
In-situ curvature measurement

Wafer A



Wafer B



- Two runs with comparable recipe and similar looking in-situ data
- But different template → significantly different strain development during AlN growth
- Result: Strong difference in wafer curvature during growth of MQW

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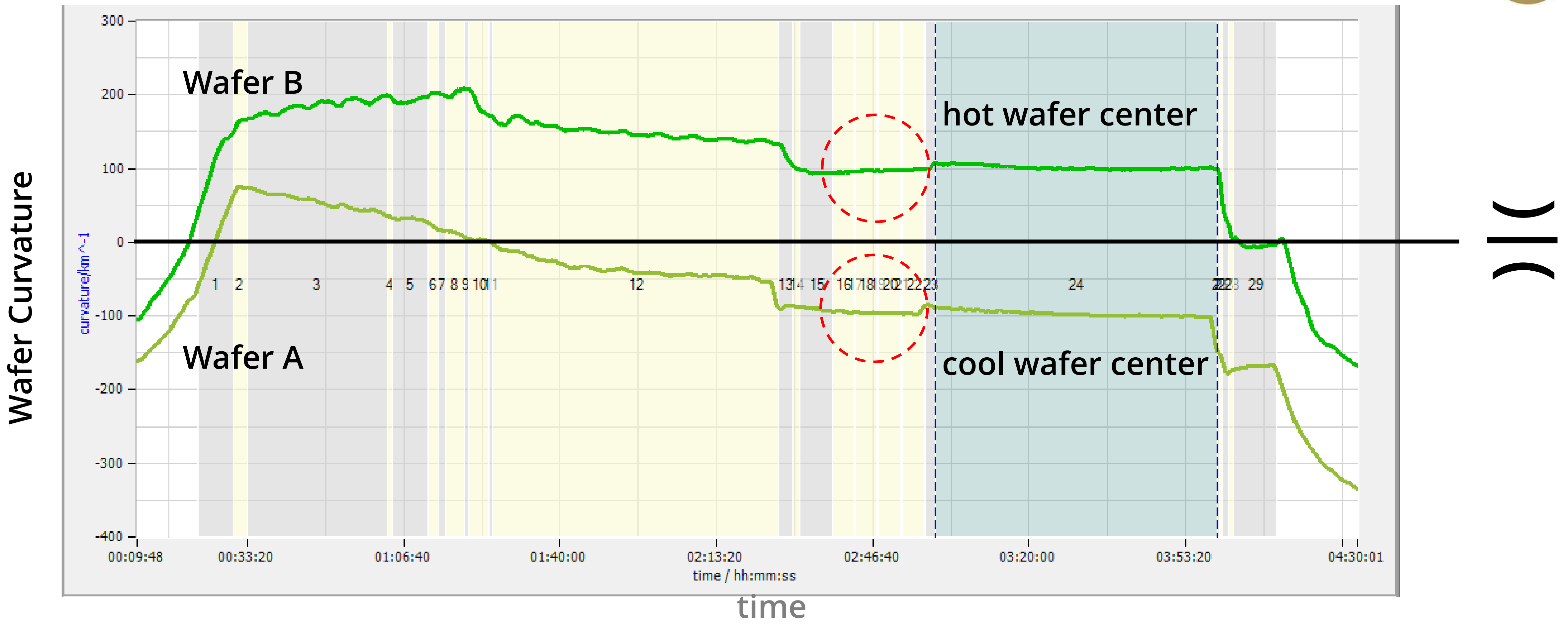
In-situ curvature measurement

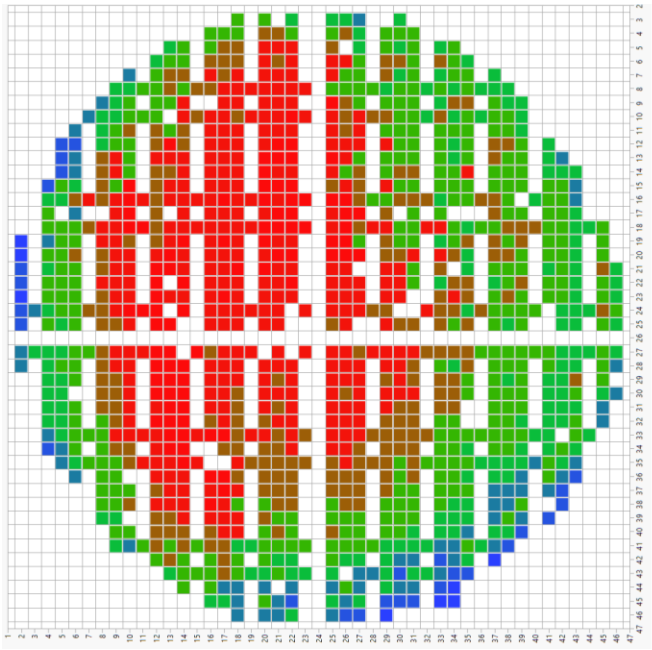


- Uniformity of LED emission can already be predicted

In-situ curvature measurement

Electroluminescence maps

Wafer A

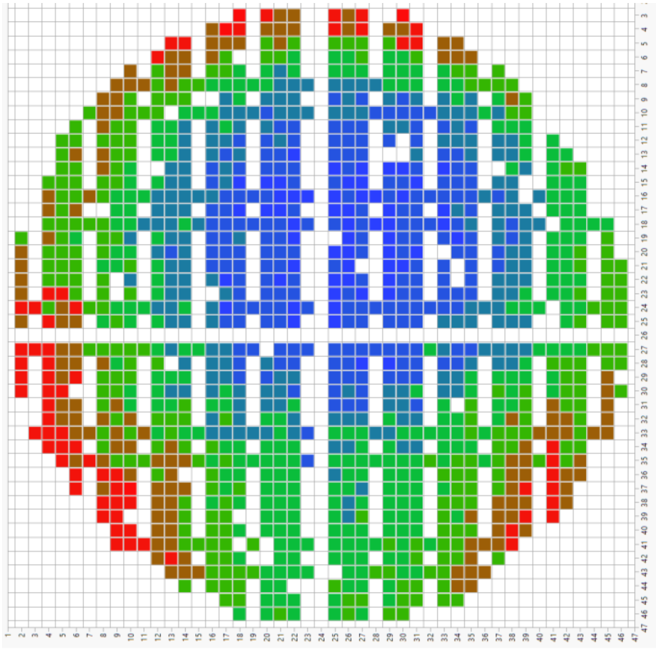


k_{AZ}= -96 km^{-1}

Peak wavelength [nm]

- 231
- 231.4
- 231.8
- 232.2
- 231.6
- 233
- 233.4
- 231.8
- 234.2

Wafer B



k_{AZ}= 97 km^{-1}

- Far-UVC LED on HTA-AlN/Sapphire template
- Longer emission λ in center

- Far-UVC LED on MOVPE-AlN/Sapphire template
- Shorter emission λ in center

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Outline

- **Motivation**
  Scope, financial aspects
- **Who are we?**
  History, markets, approach
- **Light <-> Electricity**
  LEDs, Solar cells and transistors
- **Reflectometry, deflectometry and pyrometry**
- **Case study 2, solar cells**
- **Conclusions**

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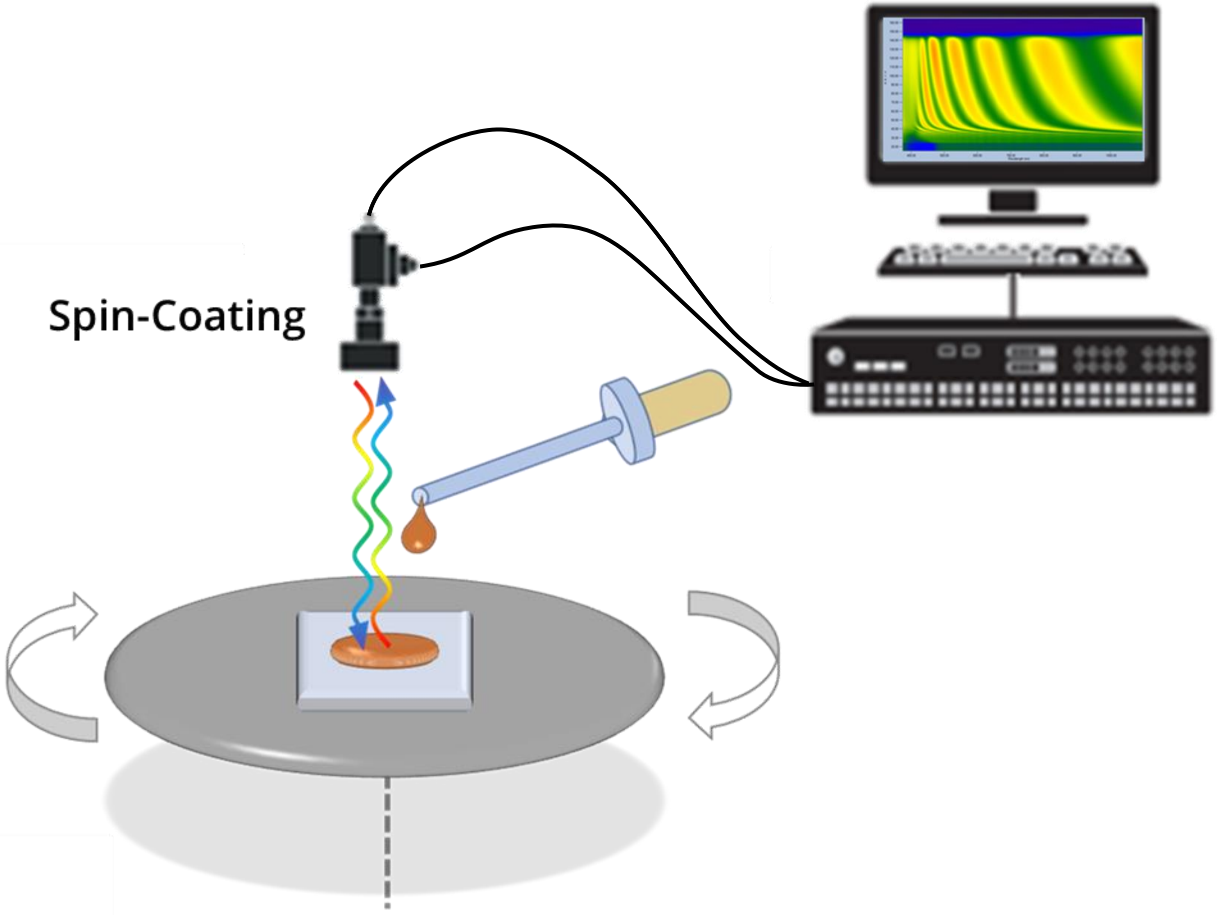
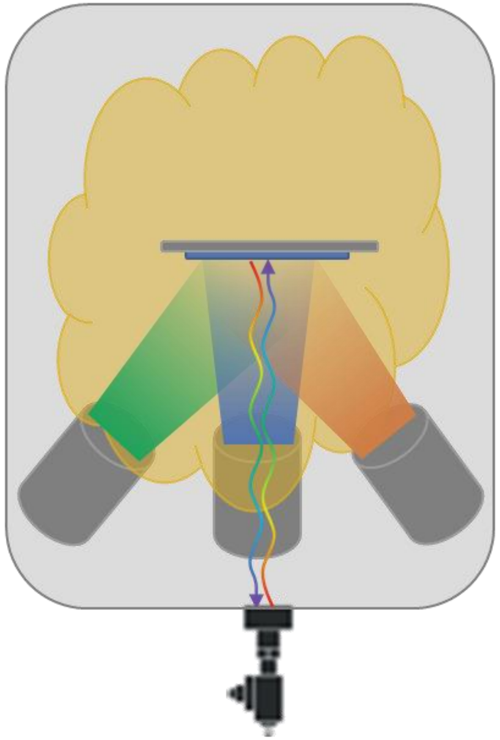
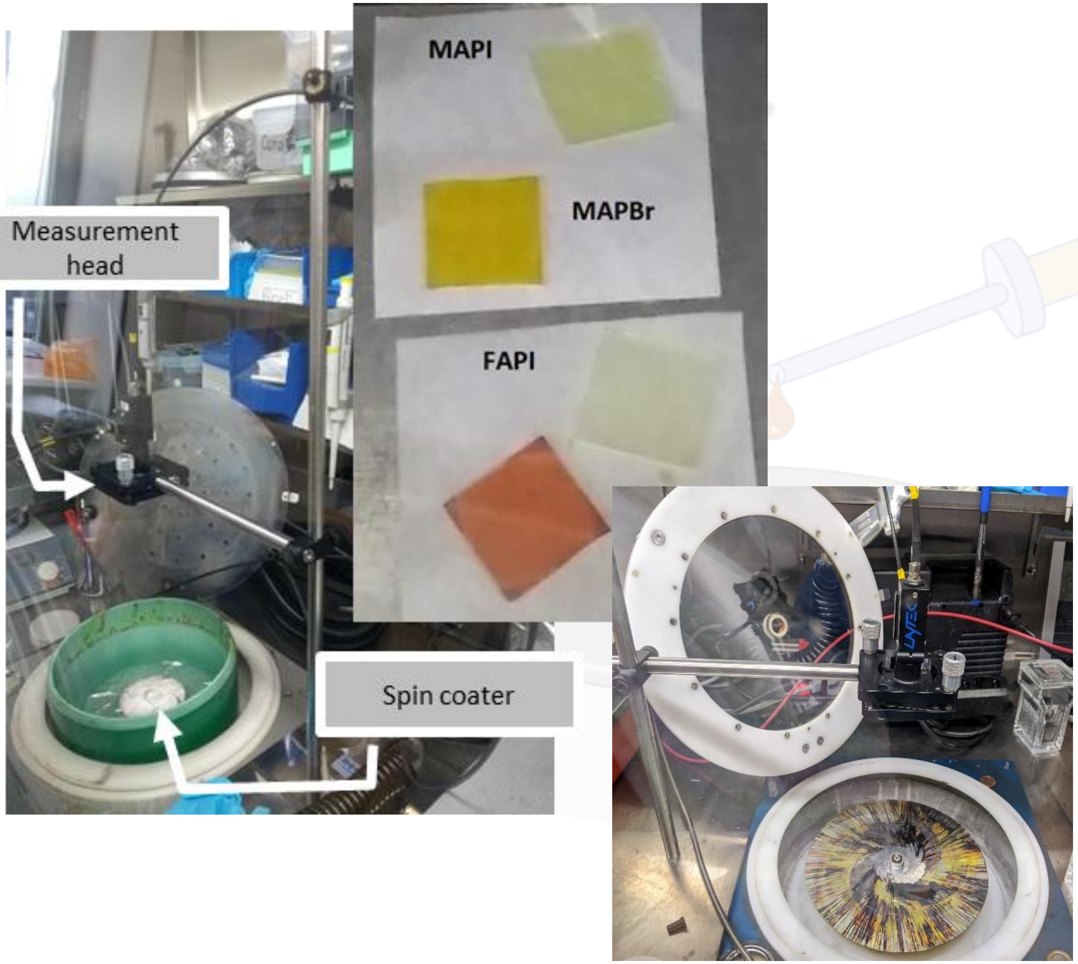
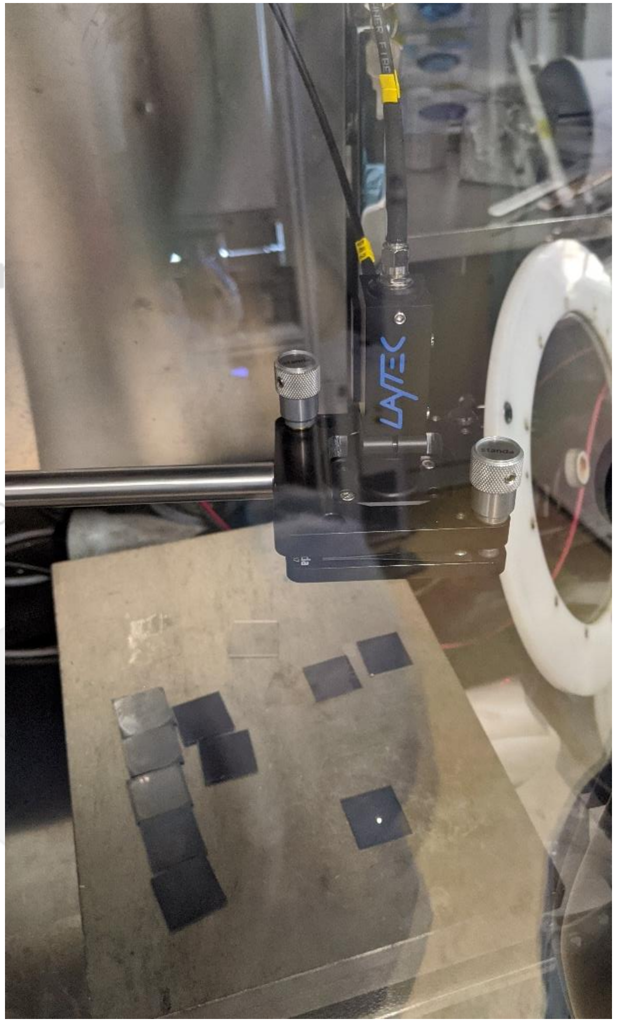
Metrology for high-efficiency photovoltaics: perovskite formation





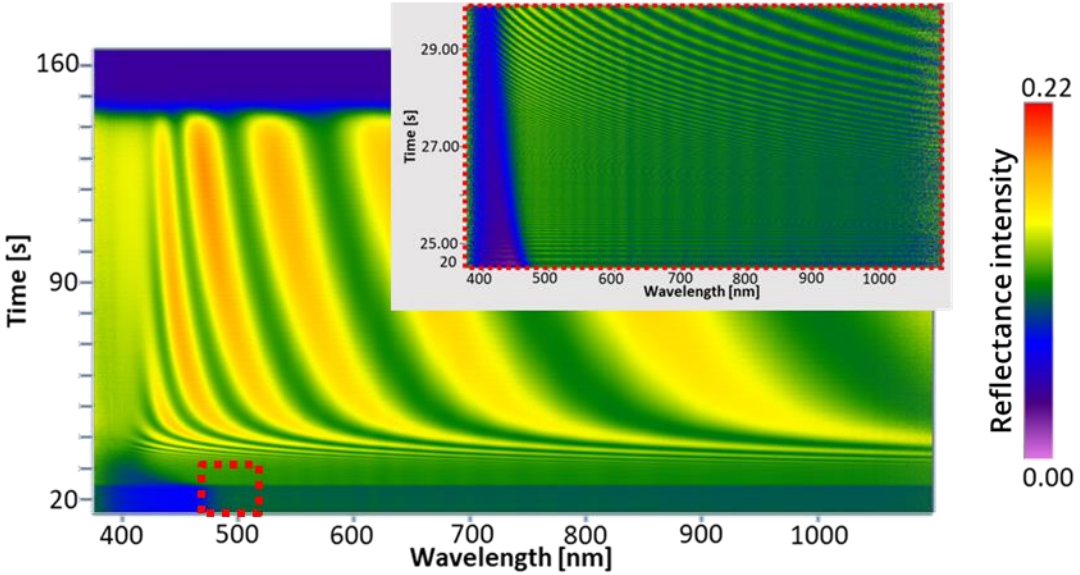
Metrology for high-efficiency photovoltaics: perovskite formation





Metrology for high-efficiency photovoltaics: perovskite formation

- ... during spin-coating



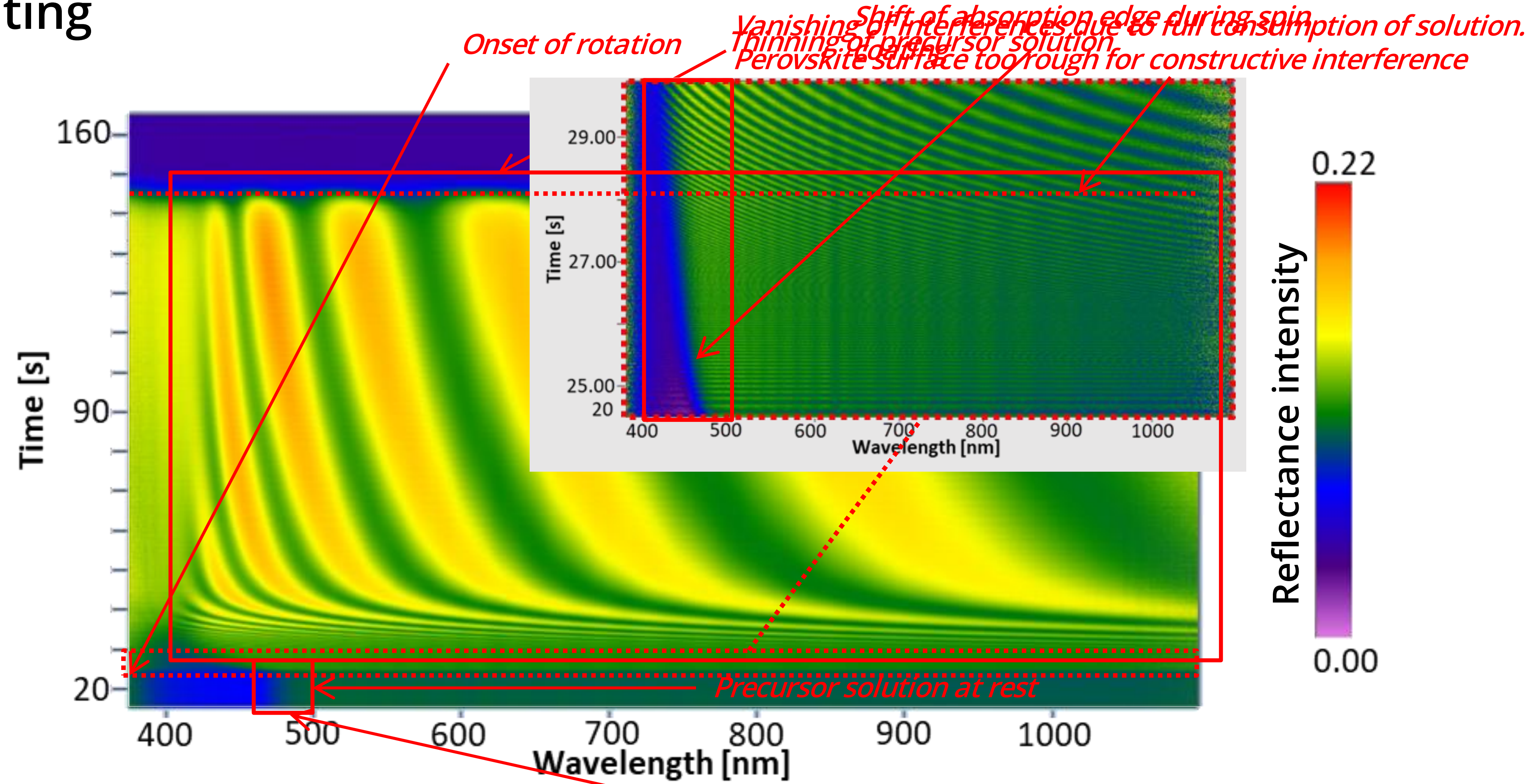
3CAT, Triple Cation Complex; Spin Coating @ 4000RPM; 180s

HZB Helmholtz Zentrum Berlin HySPRINT

C. Camus et al., Proceedings of the 47th IEEE PVSC, 2020

Metrology for high-efficiency photovoltaics: perovskite formation

Spin-coating



3CAT, Triple Cation Complex; Spin Coating @ 4000RPM; 180s

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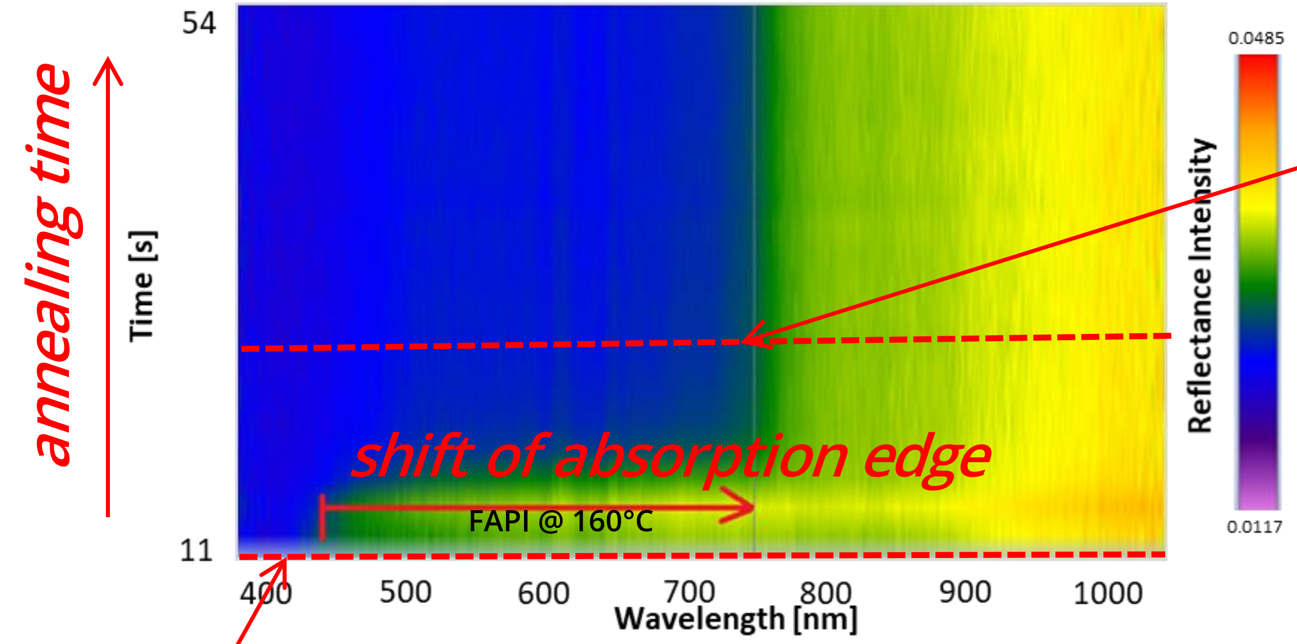
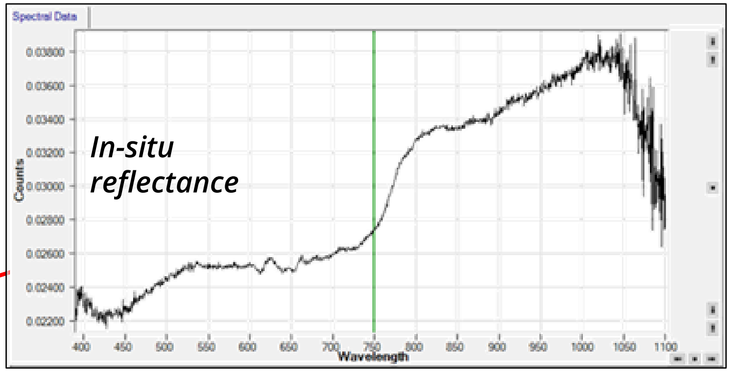
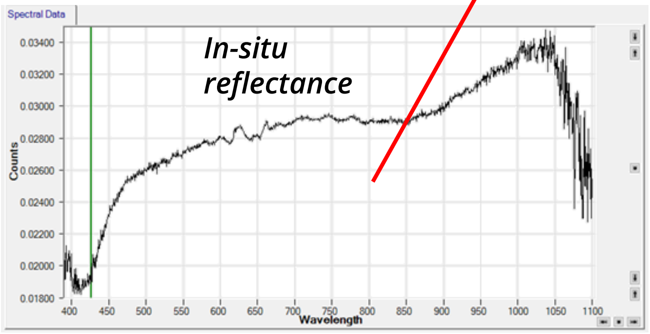
C. Camus et al., Proceedings of the 47th IEEE PVSC, 2020

Metrology for high-efficiency photovoltaics: perovskite formation

Annealing







Band gap shifts from ~450nm to 725 during annealing.

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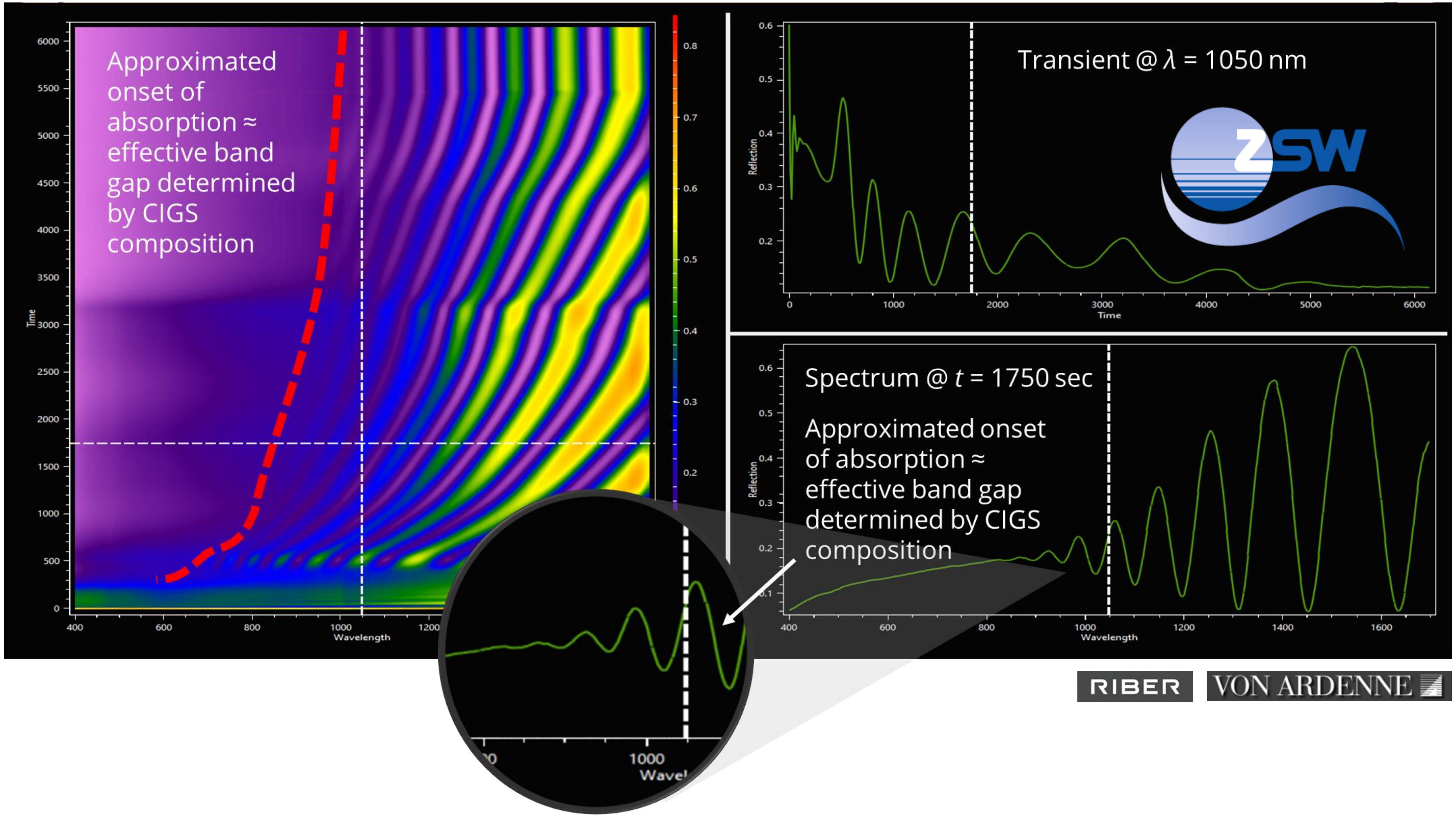
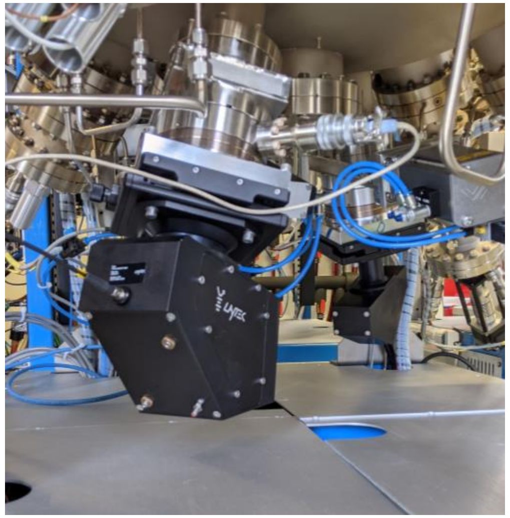
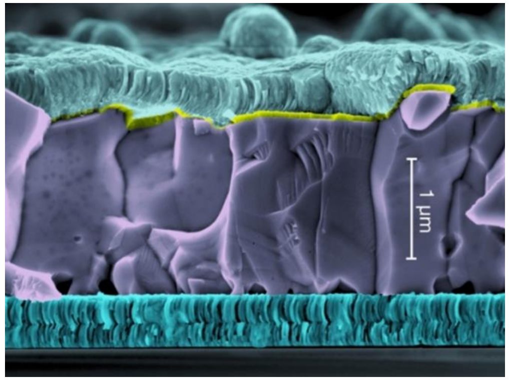
Metrology for high-efficiency photovoltaics: CIGS bandgap



RIBER VON ARDENNE





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LEDs, Solar cells and transistors

Reflectometry, deflectometry and pyrometry

Case study 3, high power transistor

Conclusions

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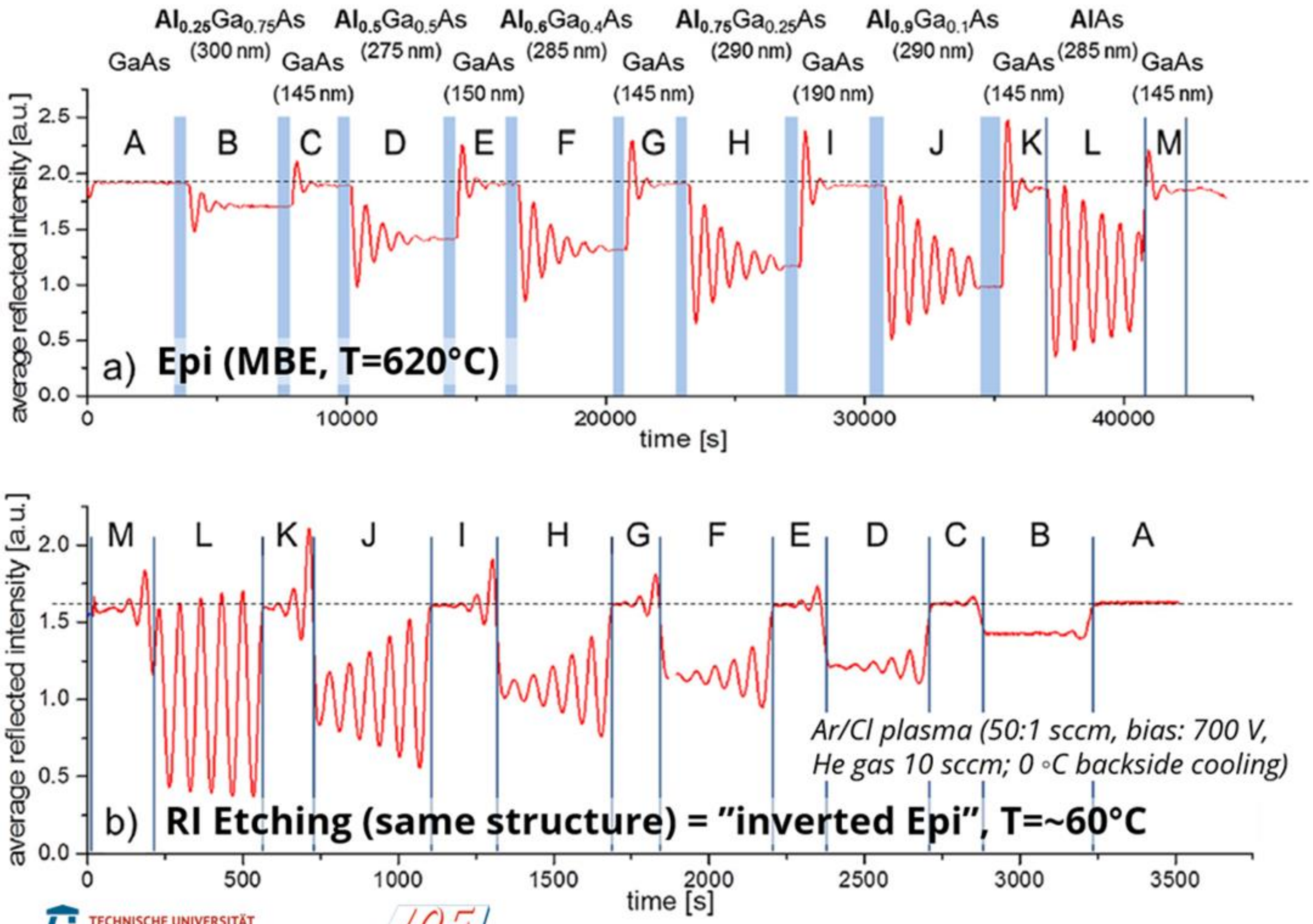
Etching monitoring

MBE

Etch



TECHNISCHE UNIVERSITÄT KAISERSLAUTERN

IOE
INTEGRIERTE OPTOELEKTRONIK & MIKROOPTIK
PROF. DR. HENNING FOUCKHARDT

- Interpreting etching as "inverted epitaxy"
- End point detection possible using interface signatures.

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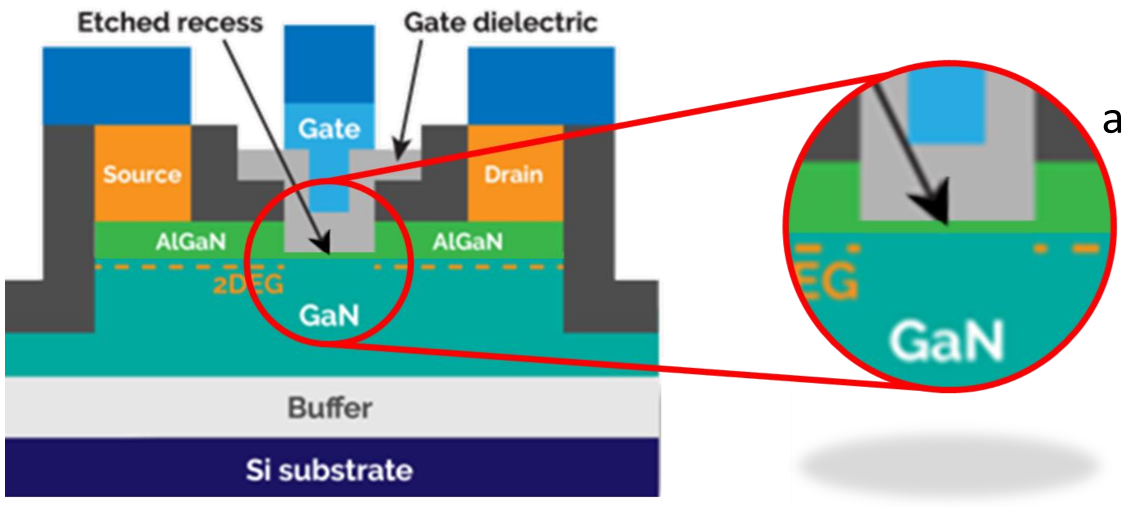
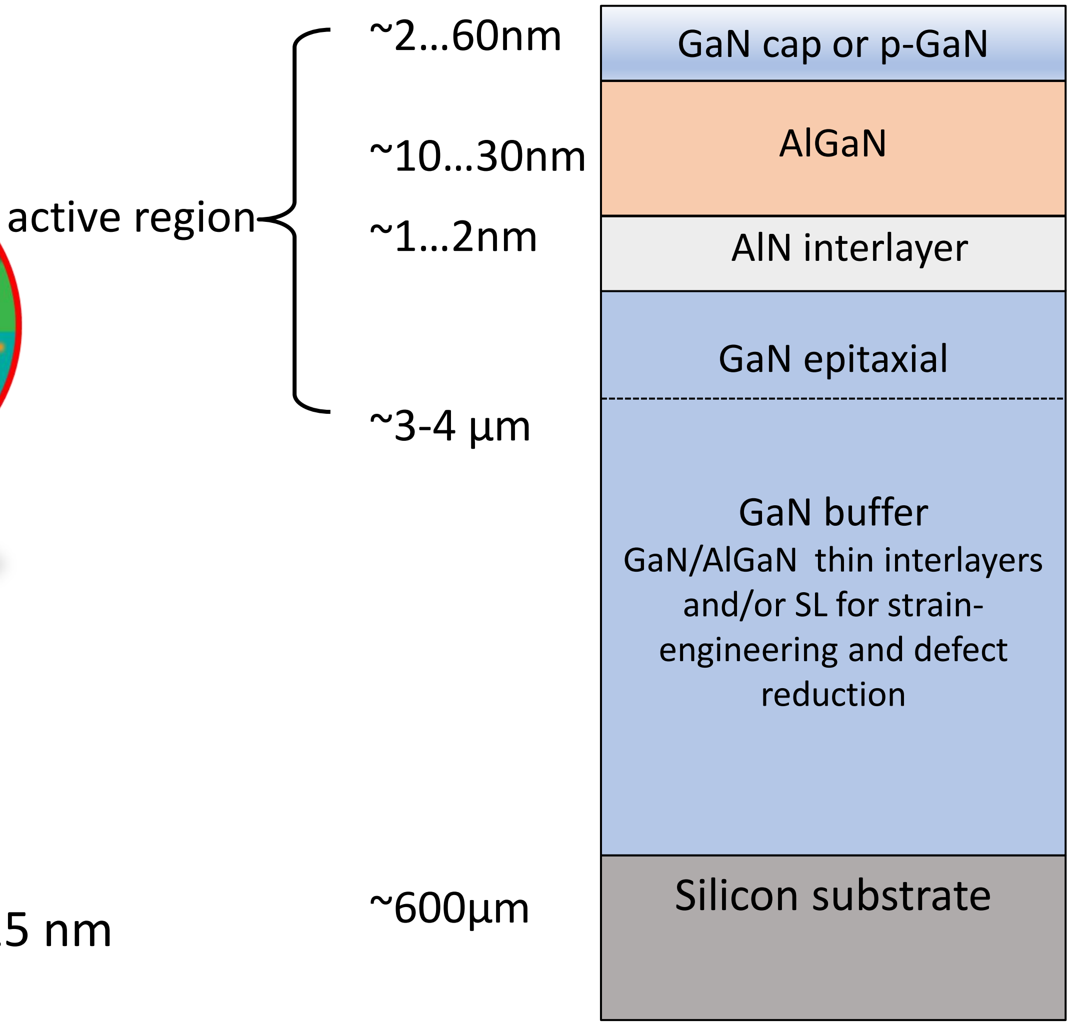
L. Barzen et al.; Applied Surface Science 328 (2015) 120–124

Etching monitoring: GaN/Si HEMT (high electron mobility transistor)



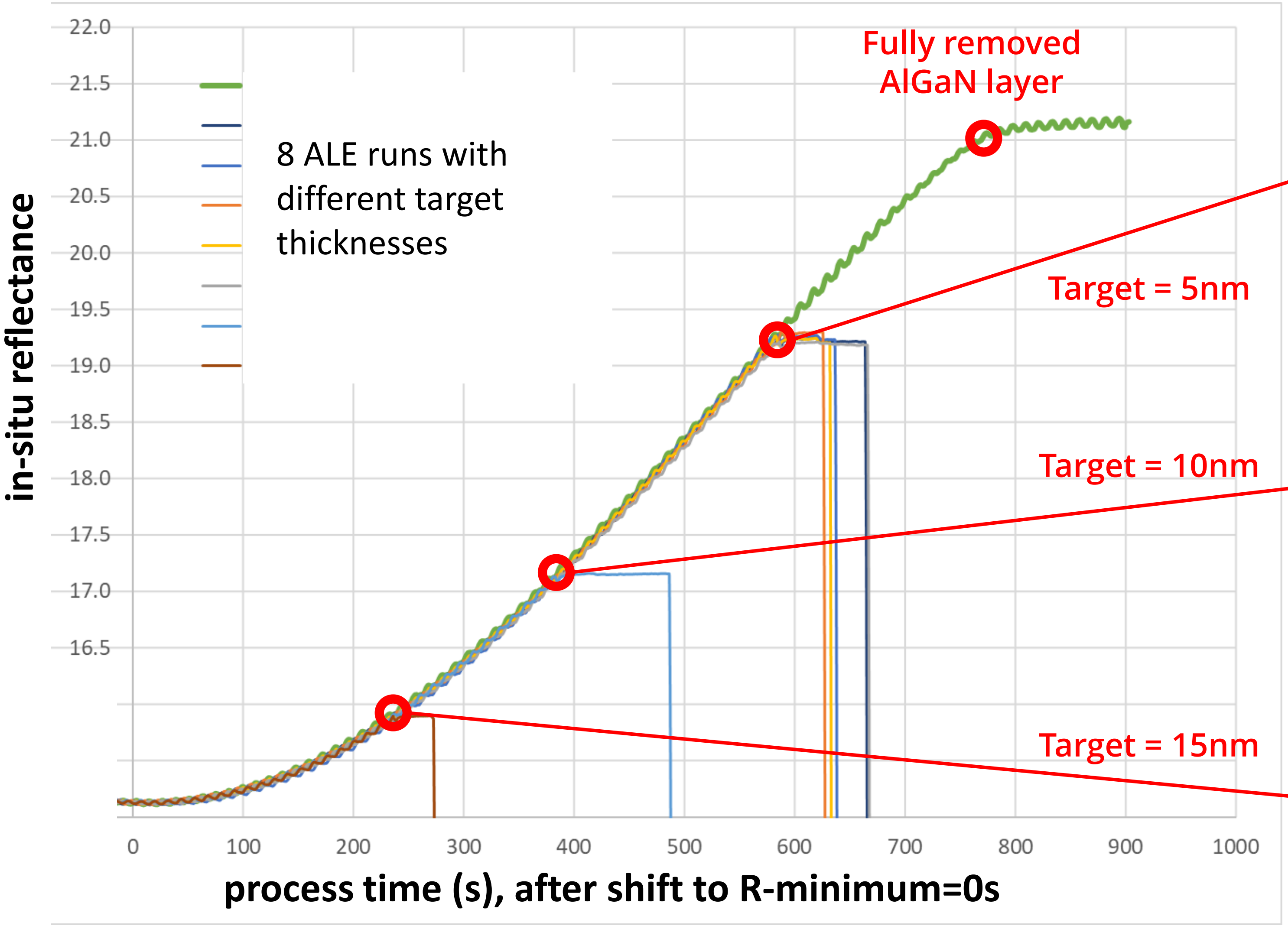
Typical (simplified) GaN/Si HEMT layer structure

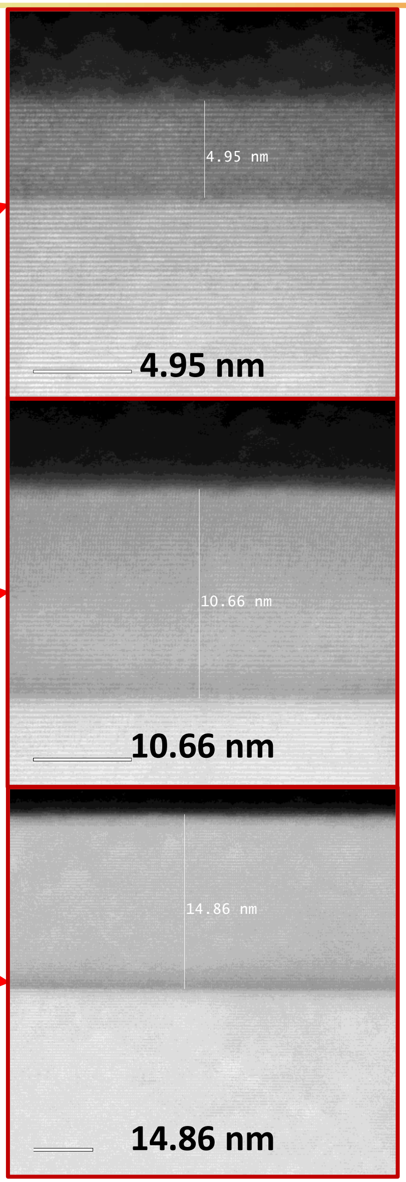


- Atomic layer etching into AlGaN layer
- Target (remaining) thickness: 5, 10 and 15 nm

K. Haberland et al.; Photonics West conference (2023)

Etching monitoring: GaN/Si HEMT (high electron mobility transistor)





TEM

- **ex-situ**
- **destructive**

OXFORD INSTRUMENTS

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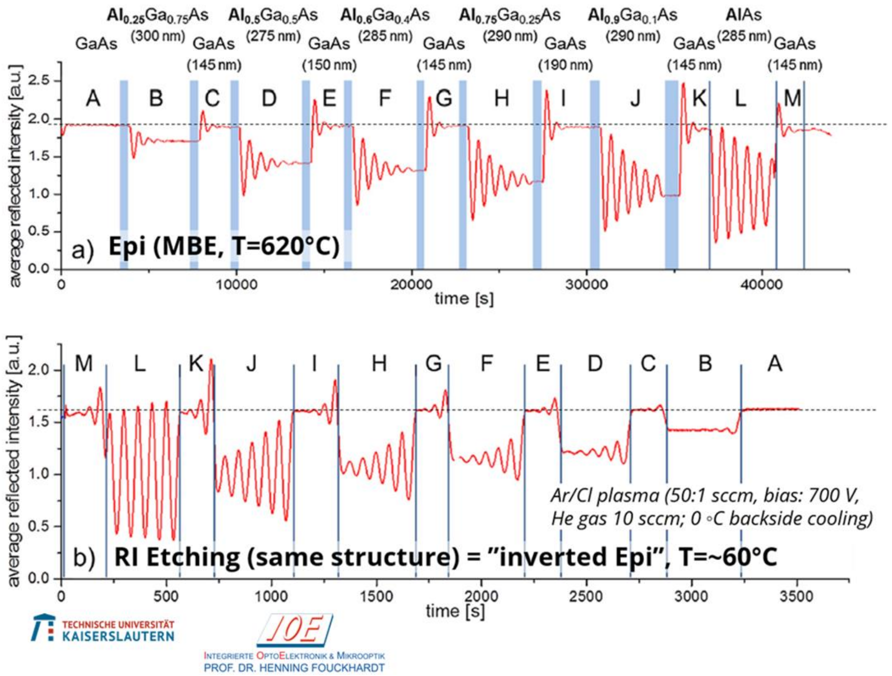
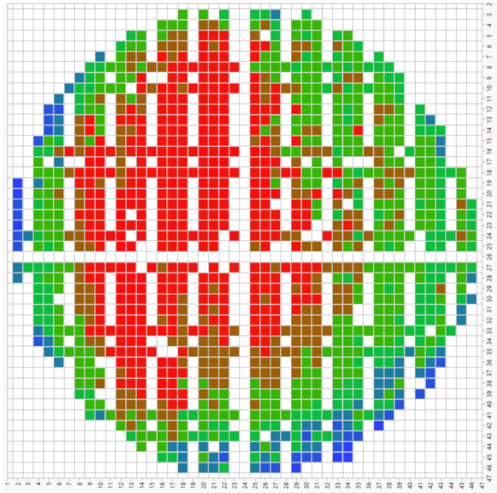
K. Haberland et al.; Photonics West conference (2023)

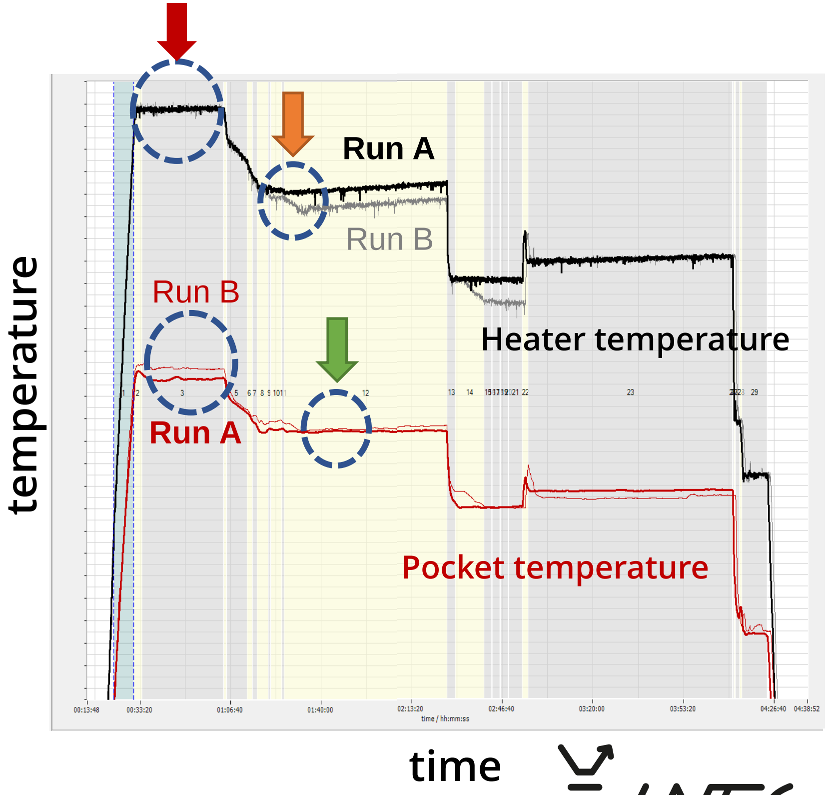
Conclusions

- Integrated optical metrology, indispensable for high-yield energy production.

- Reflectometry for refractive index, growth/etch rate, etc.
- Deflectometry for wafer bowing quantification.
- Pyrometry for in-situ temperature control.







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Thank you!

Knowledge is key

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Rebound effect

Figure 4: Results of rebound effect on the average US-household annual electricity use for lighting. Original data from [HIC-15] modified by G. Zissis

Figure 4 shows the impact of the rebound effect under 2 scenarios – Scenario 1: Individual households don't use more light as the cost of lighting decreases but population growth and increasing in housing size over time result in increase of energy demand for lighting; Scenario 2: Energy use increases over time because individual households demand more light as the cost of lighting decreases and lit areas increase as a result of population and housing area growths. Both scenarios show that the LED "effect" will vanish somewhere in between 2065 and 2070. This is not acceptable; solutions are then necessary to solve the issue. One potential solution consists on switching to smart human-centric lighting driven by both "application efficiency" and quality of light. **This just means that next gen lighting systems should provide the "Right Light" with the best efficiency and quality, when and where it is needed.**

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