SEMICON EUROPA

FORWARD
AS ONE

Go faster for process control : Enhanced sensitivity of ellipsometry imaging for deviation detection

Subtitle Goes Here Lorem Ipsum

March 8, 2021

semi

LTM
LABORATOIRE DES TECHNOLOGIES
DE LA MICROÉLECTRONIQUE

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LTM Tasks in MadeIn4

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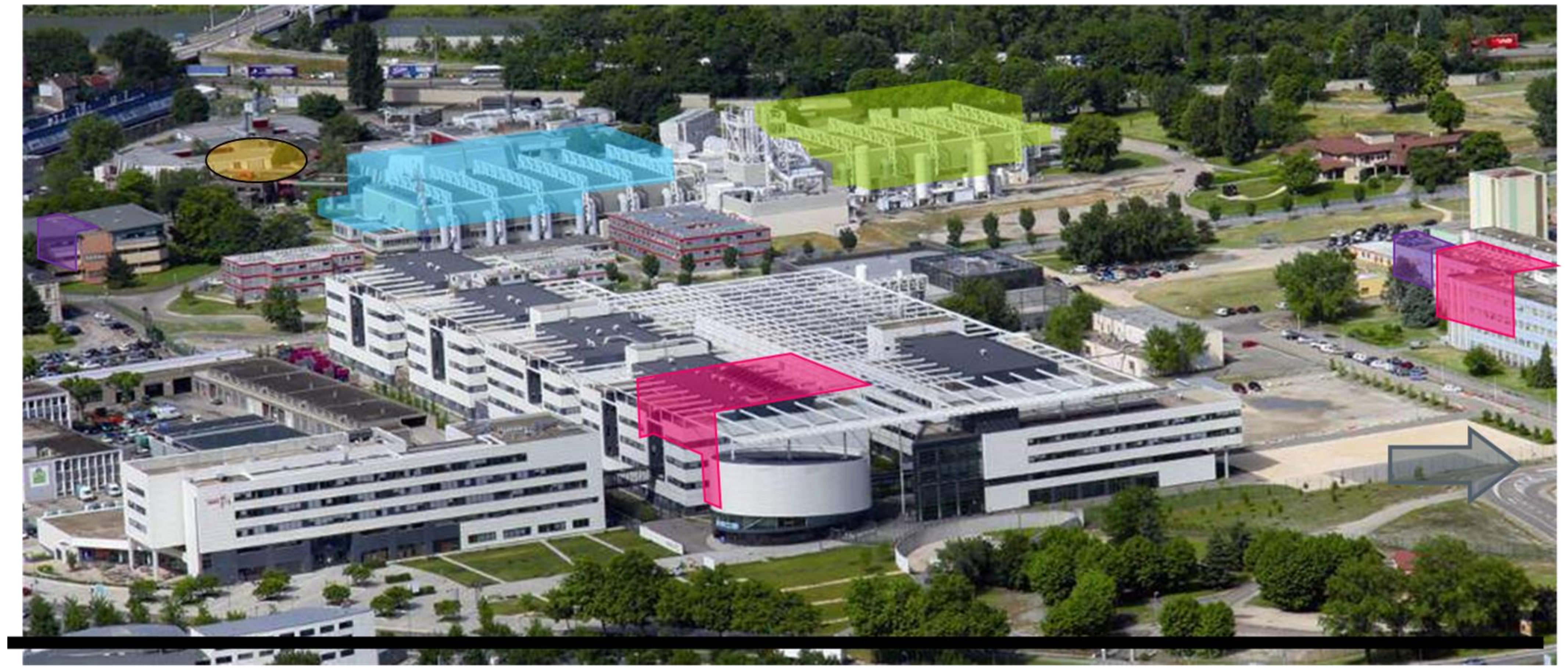
LTM Academic Lab

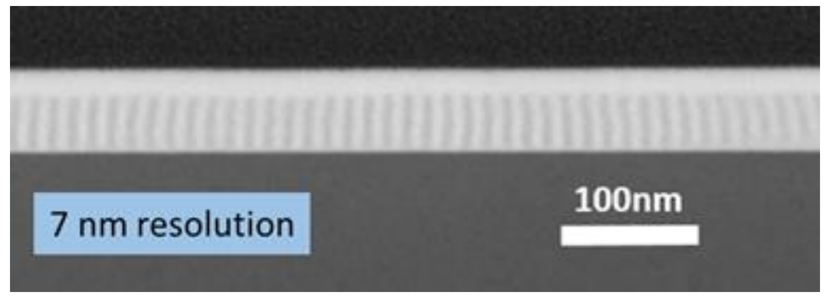
- ☐ Joint research academic lab

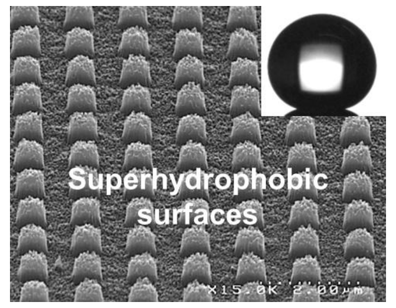
  CNRS/University Grenoble Alpes (UGA)

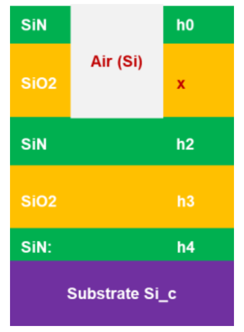
  80~100 persons, two teams
- ☐ Prospect Team:
  - ✓ Plasma etching
  - ✓ Material integration
- ☐ Minasee Team:
  - ✓ Micro and Nanotechnologies for Health
  - ✓ Micro and Nanotechnologies : Lithography and Metrology

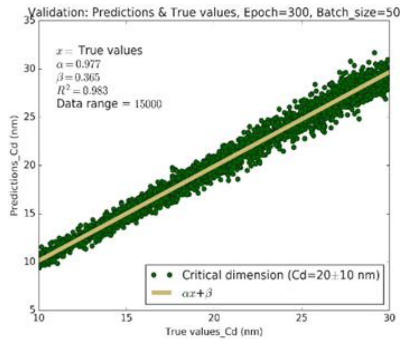


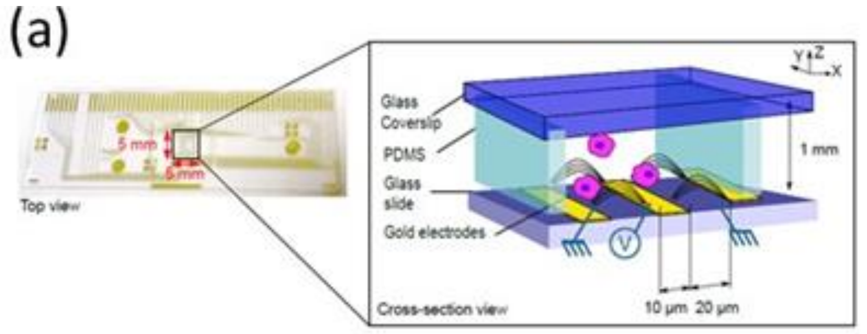
🟦 CMOS 200
🟩 CMOS 300
🟥 PTA: Plateforme Technologique Amont
🟪 Biosanté

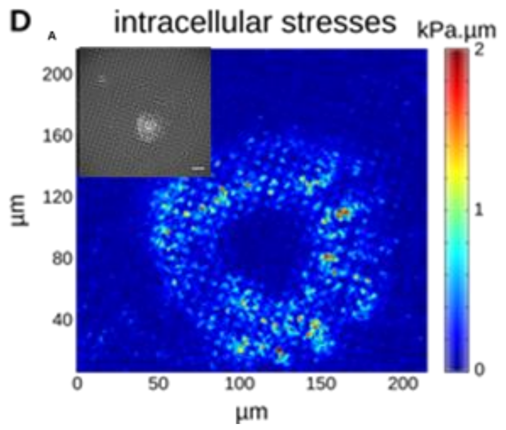


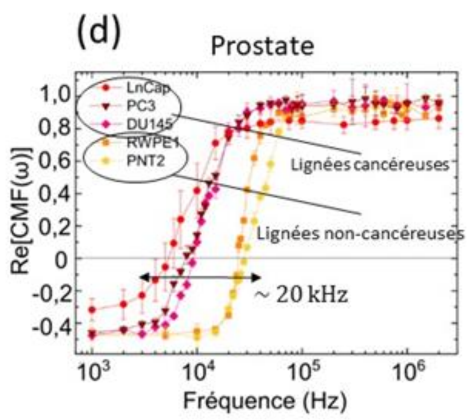


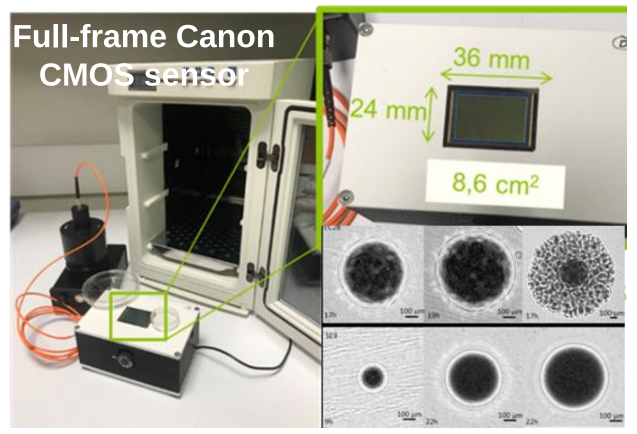








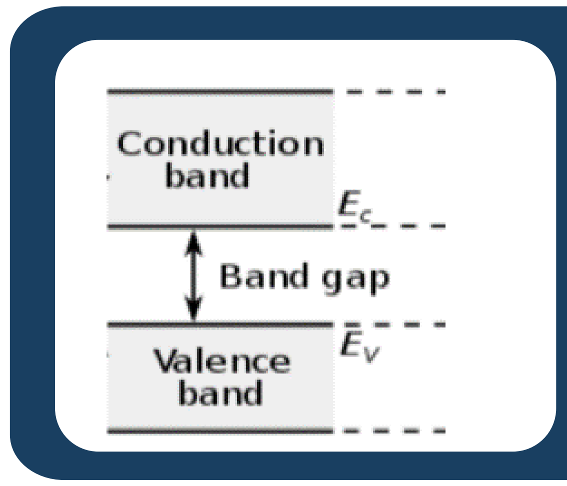




Industry 4.0 context: **GET MORE** out of metrology steps

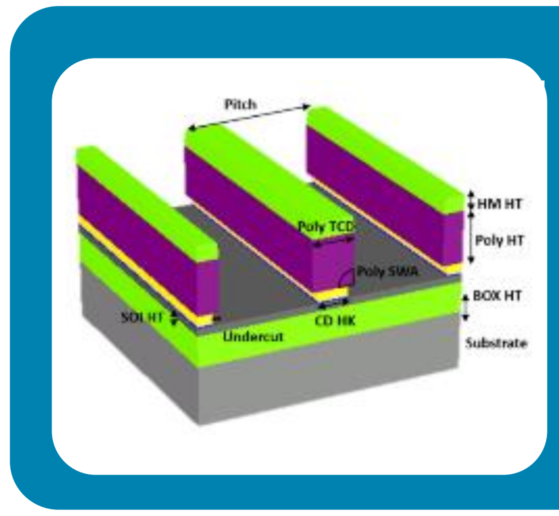
GET MORE out of what we already get from metrology steps

GET MORE



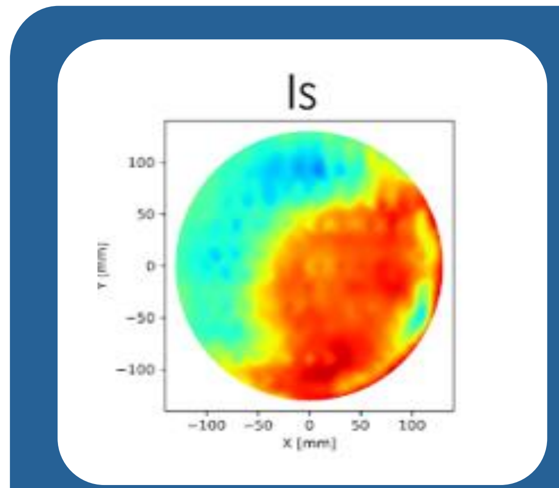
1) **Increase Knowledge** **(MADEin4 booster 1)** → New parameter

- New materials intoduced in fab to support technology diversification
- New characteristics needed for direct analysis inline
- Mutualise metrology techniques to get new informations



2) **Increase Robustness** **(MADEin4 booster 1)** → New approach for Hybridization

- Benefit from different sources of metrology techniques to get more accurate measurements
- Use proper smart algorithm based on NN to enhance quality from combinaison of inline raw signal and collected data



3) **Go Faster** **(MADEin4 booster 2)** → New approach for process deviation

- Model based techniques are very time and ressources consuming
- **Model less approach is now needed even at R&D phase when structures and materials are not fully defined**

Metrology and process monitoring

- InLine metrology:
  - Metrics for process development and control
  - If metric in confident interval ➔ Go else NoGo

- Metrology tools:
  - Not destructive except for R&D purpose
    - Wasted wafers cost a lot

  - Small metrologies dies in dead areas of wafer products
    - Located in cutting path of the wafer, wasted area cost a lot

  - **<u>High sensitivity</u>**, high accuracy, reproducibility on measured metric
    - Topography (Interferometry), Strain (Interferometry) : No modeling needed
    - Patterns dimensions (SEM) : No modeling needed once calibrated (threshold tuning)
    - Thicknesses (**Ellipsometry**), Patterns profile (**Scatterometry**) : **<u>Model dependent</u>**

Ellipsometry and process deviation ➔ Get More

Ellipsometry principle

Ellipsometry measures the **polarization change of the light** after reflection onto a flat surface

Necessitates a light source, a polarization state generator (PSG), a polarization state analyzer (PSA) and a detector

Academy

At LTM: Phase modulated ellipsometer, working at 50 kHz

- Photo Multiplier Detector (PEM): Each wavelength recorded in a sequential way (spectrometer)
- PEM: recording rate down to 50 ms at one wavelength but >2mn for a spectroscopic scan
- Low throughput in spectroscopic mode, very high throughput at one wavelength

Industry

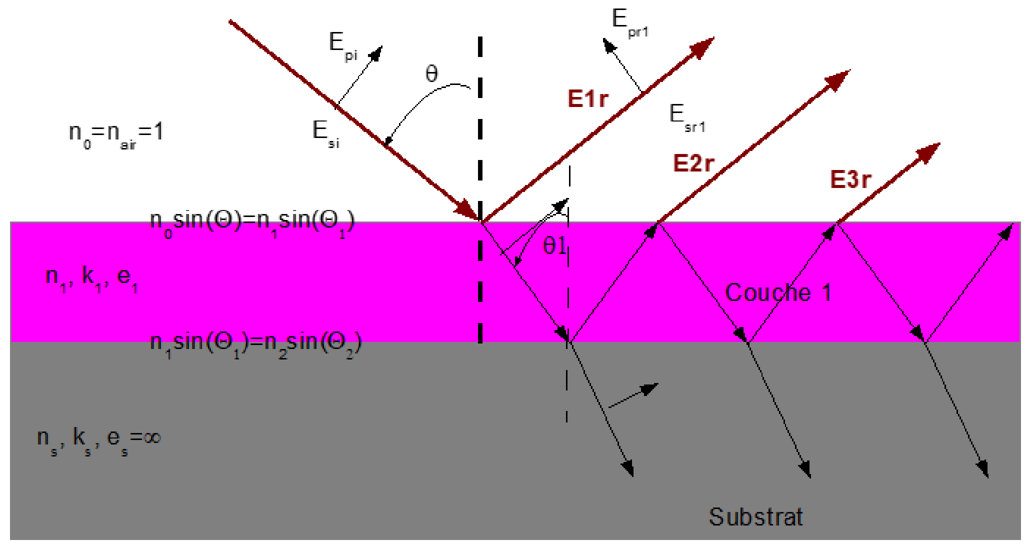
At ST: Rotating polarizer, working at 9 Hz

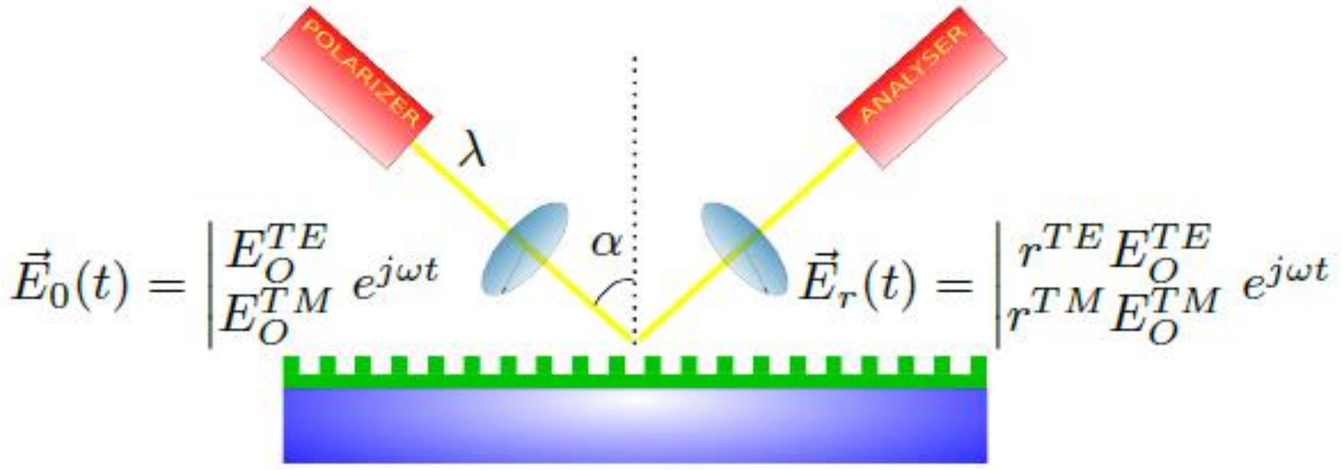
- CCD Detector: All wavelength recorded at once
- CCD: Spectroscopic recording rate close to 1s
- High throughput ➔ Highly efficient for InLine metrology

Ellipsometry/Scatterometry

- Change in the **polarization state** is what is measured
- Raw data are not Metrics: **Indirect measurements**
- To get metrics: **Modeling** is mandatory
  - Planar layers : Modeling ➔ Ellipsometry: Thicknesses, Optical indices, nb of layers
  - Patterned grating : Modeling ➔ Scatterometry: Ellipsometry + Patterns shape
- Scatterometry **modeling**:
  - Time consuming:
    - Necessitate deep development to be operational
    - Long computation time to solve a new problem
- How to detect errors or deviations more quickly: bypassing the modeling step

Artificial intelligence algorithms once trained give instantaneous prediction (inference)

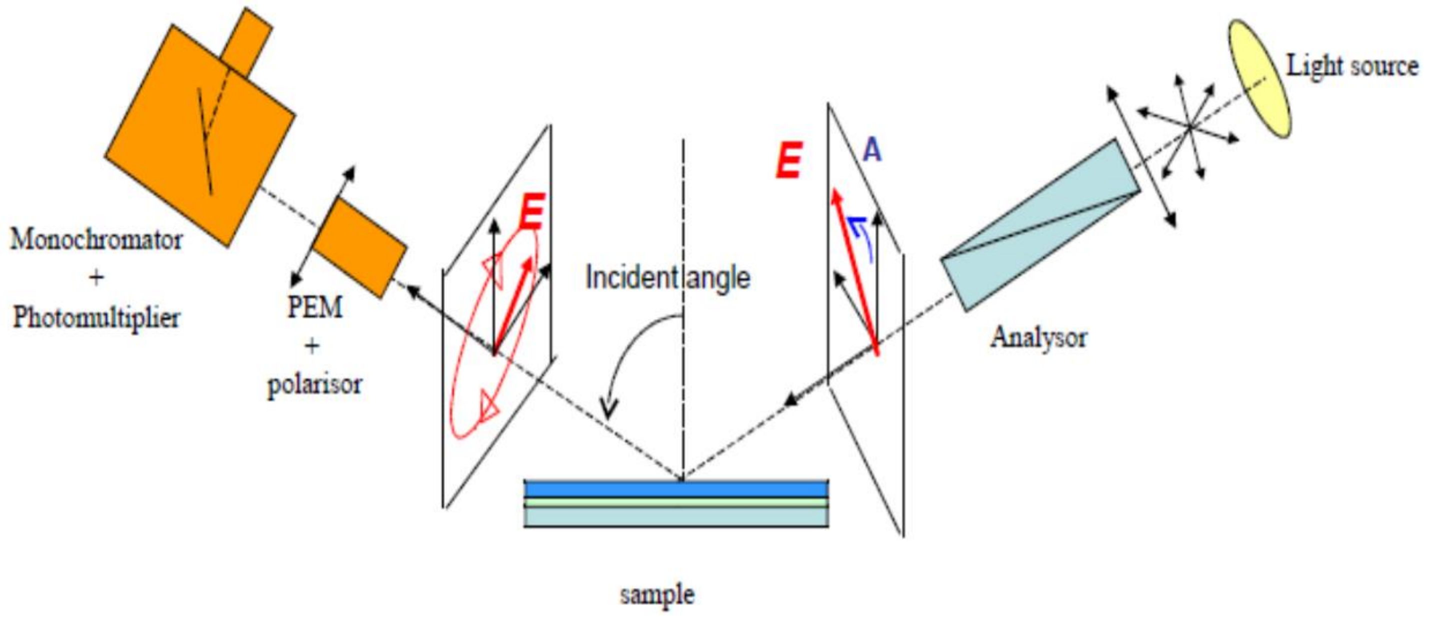


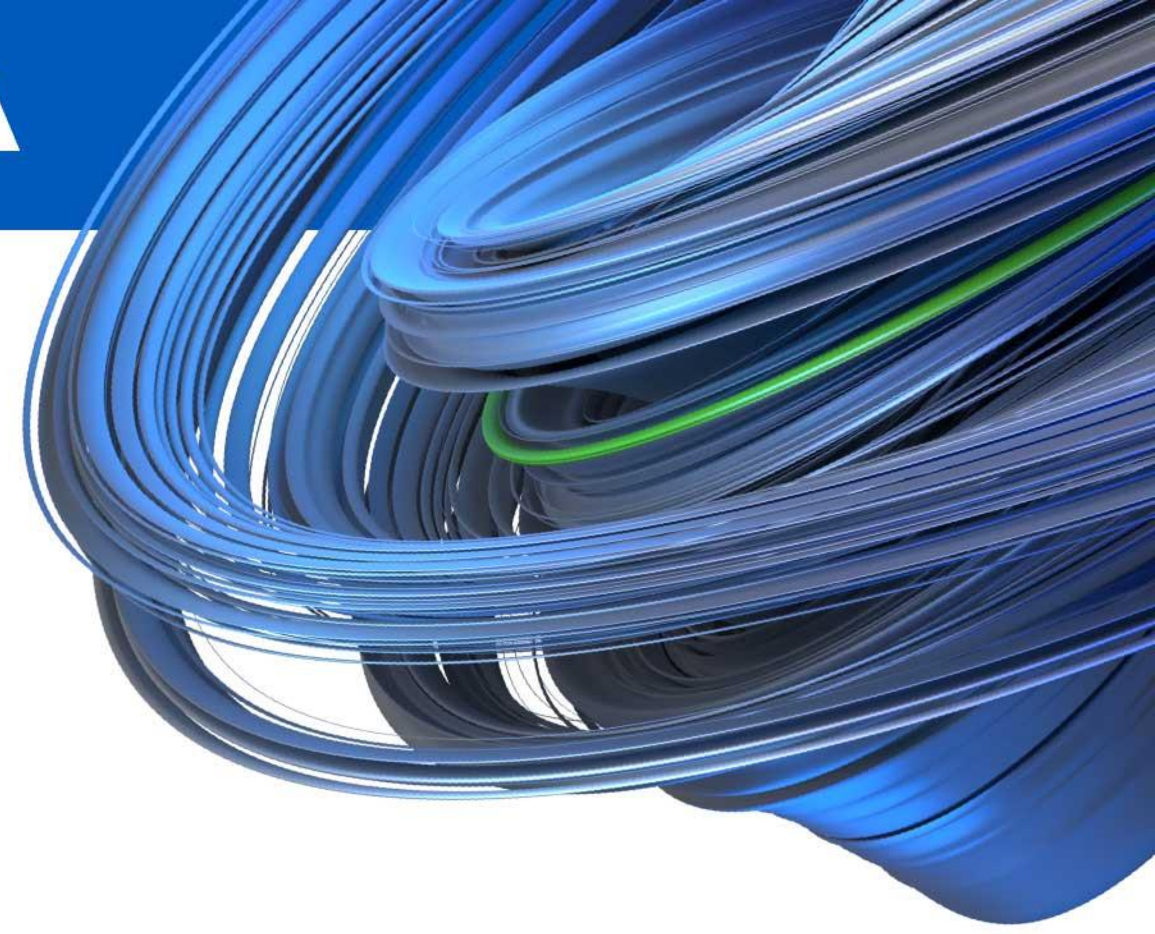


$$\vec{E}_0(t) = \left| \begin{matrix} E_O^{TE} \\ E_O^{TM} \end{matrix} \right. e^{j\omega t} \qquad \vec{E}_r(t) = \left| \begin{matrix} r^{TE} E_O^{TE} \\ r^{TM} E_O^{TM} \end{matrix} \right. e^{j\omega t}$$

IMPACT Ellipsometer @ LTM

- IMPACT: Characterization cluster of three chambers (XPS, Raman/photolum, Ellipso)
- Broadband ellipsometer:
  - From 150nm up to 2000 nm by ellipsometry (150nm-11µm by hybridization with MIR polarimeter)
  - 300mm wafer mapping capability0
  - Stage under vacuum
- Step and repeat mode to cartography a wafer
- Limited number of measured spots
- Smallest Spot size: 300 x 300 µm

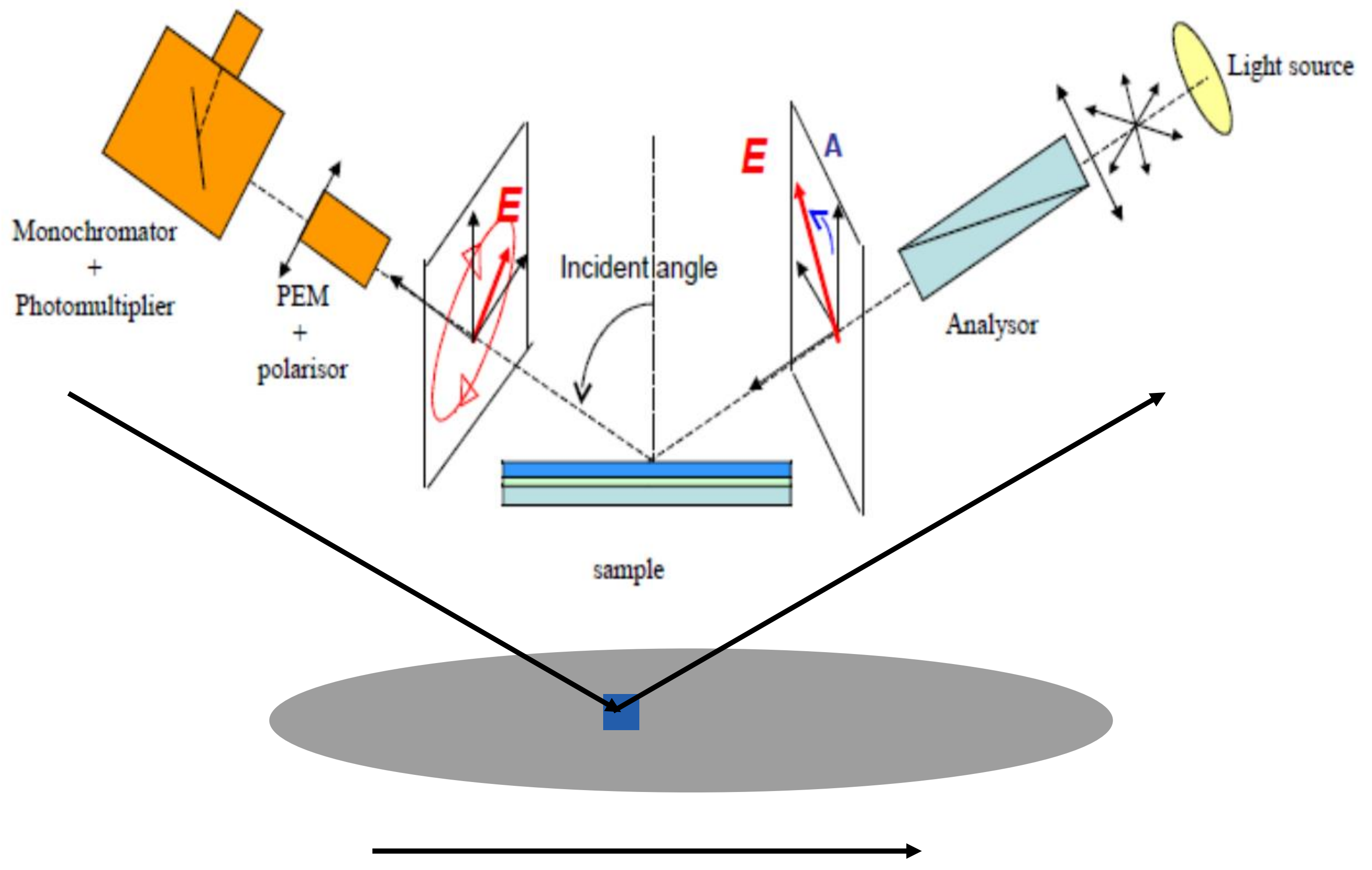


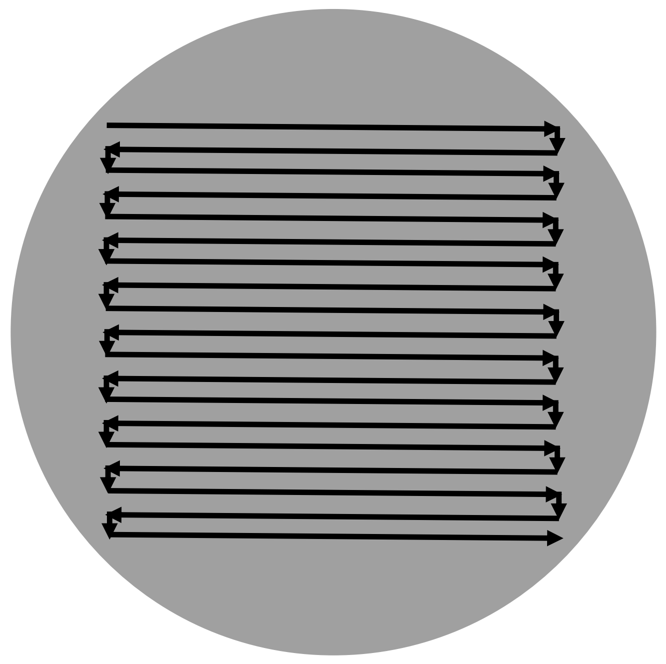


Imaging using Ellipsometry

- New acquisition scenario: The raster Mode
  - Collaboration with Horiba to upgrade the hardware of the tool
  - Principle: Measuring in real time (every **50 ms**) the variation of the raw signal while the stage is moving at a known speed
  - Reconstruction of the image by adjusting the recorded signature with the position in time
- <u>Low Throughput</u> but high resolution
  - 300 µm pixel size in X and Y
  - For a 200x200 mm scan field: 665 x 665 pixels
  - **442 225** measurements:
    - 6 hours of measurements in raster mode
    - Estimated at 15 days in step and repeat mode…
- Possible to speed up down to 10 ms per pixel thanks to the PM recording rate

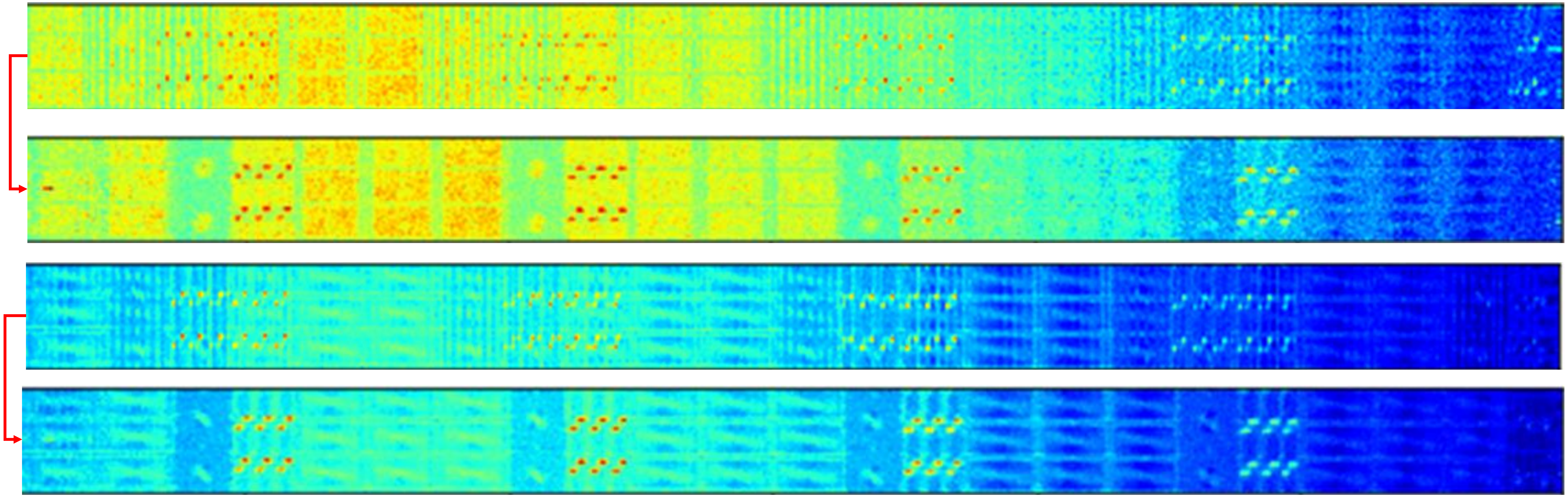
But yet limited by the stage displacement velocity





Imaging using Ellipsometry

- Image generation and aberration corrections
  - Aberration due to mismatching between real position and targeted one
  - Aberration due to local hard point in the stage displacement



Aberration compensation

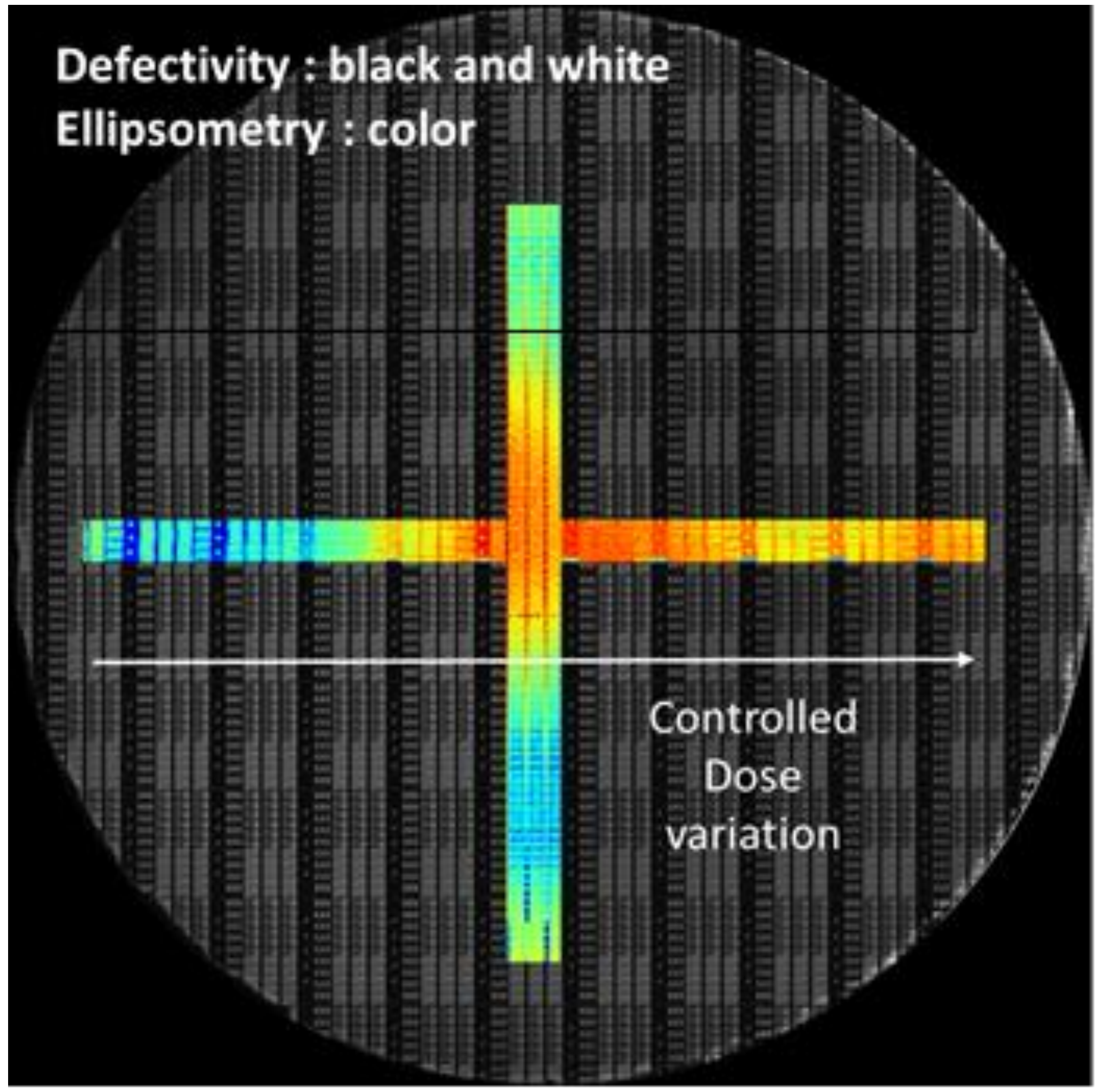
Aberration compensation

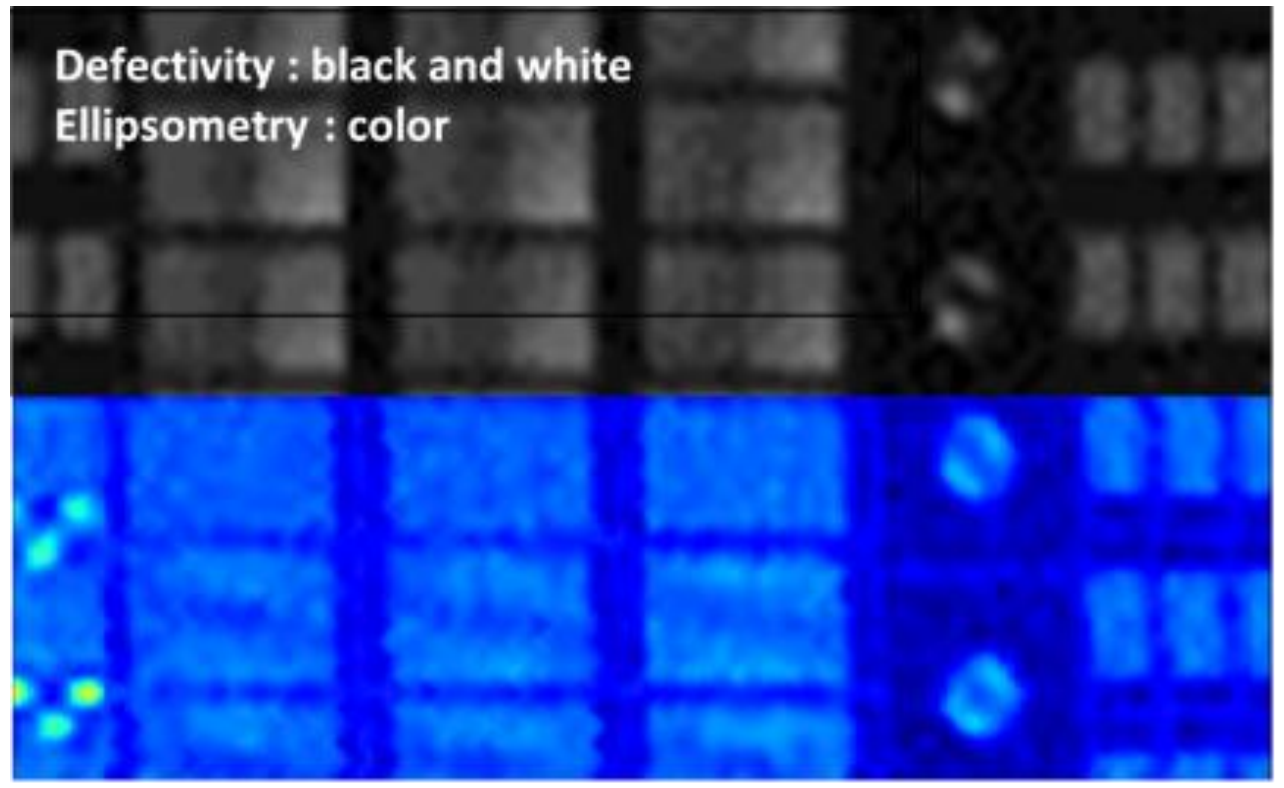
Imaging using Ellipsometry

- Augmented information compared to defectivity imaging

- At the wafer scale:
  - Center to edge variation (undesirable)
  - Sensitive to dose variation (Controlled during the process)

- At the local scale
  - Resolution sufficient when compared to defectivity images

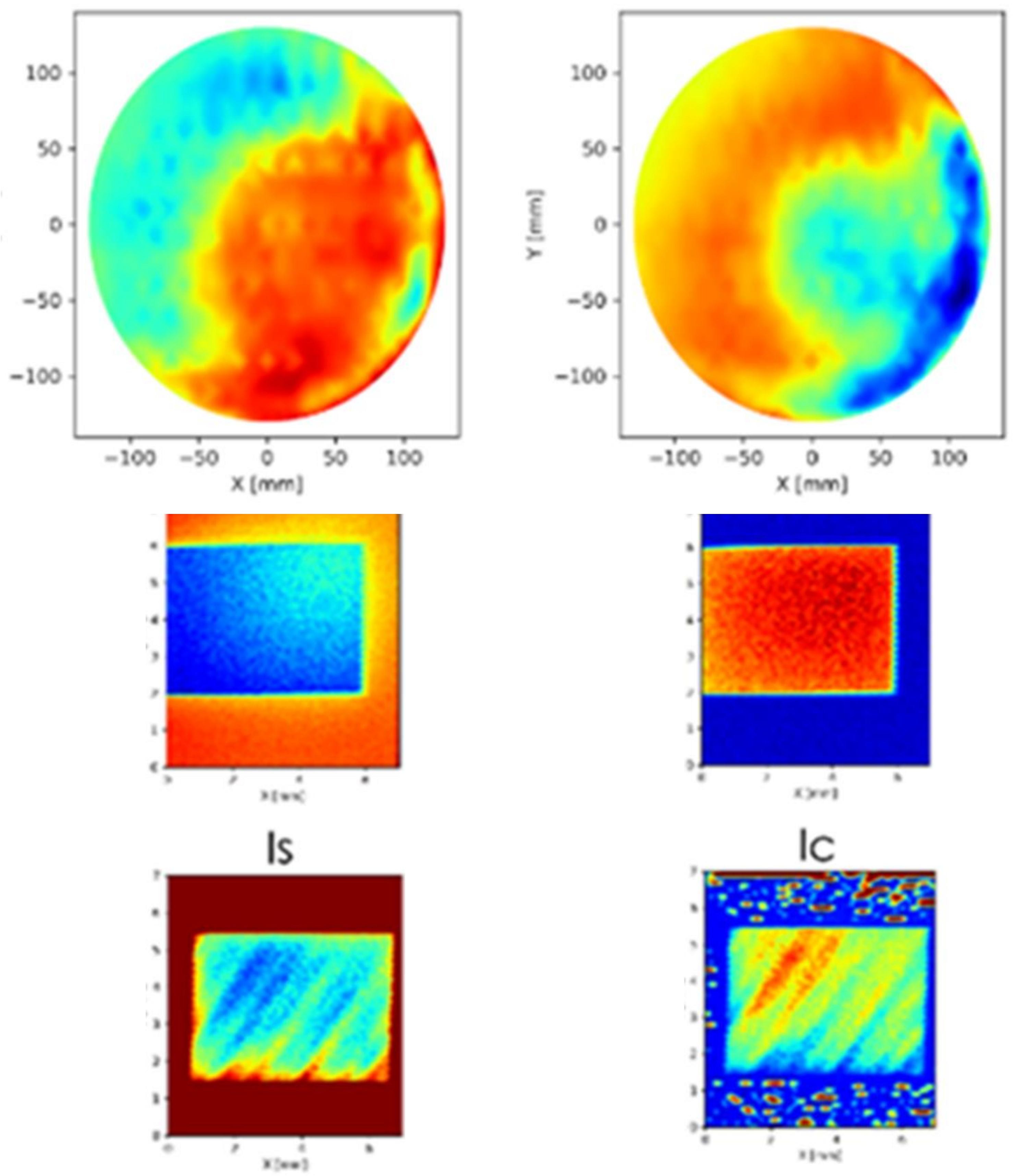




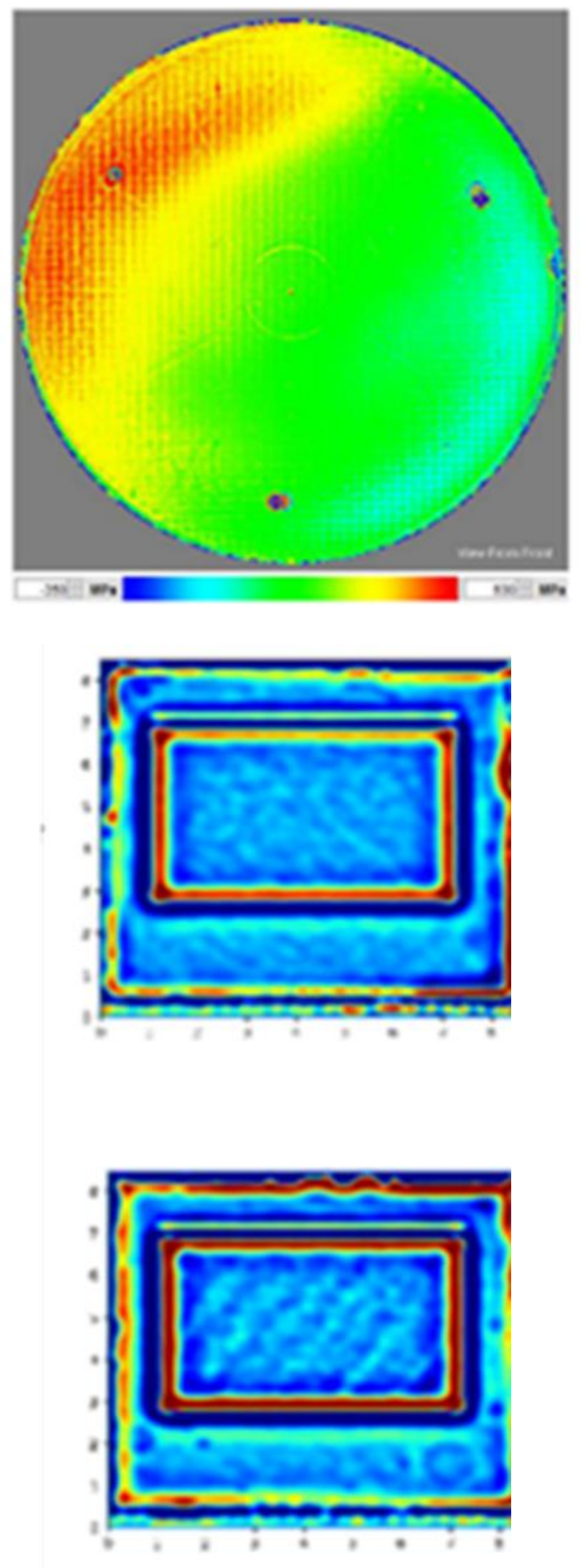
Is ellipsometry imaging resolution sufficient to detect defects?

Imaging using Ellipsometry

- Is ellipsometry imaging resolution sufficient to detect defects?
- Sensitivity at the full wafer scale
  - **Stress properly imaged**
  - 2 “channels” by ellipsometry
- Sensitivity at the die scale
  - **Striation properly detected**



Ellipsometry



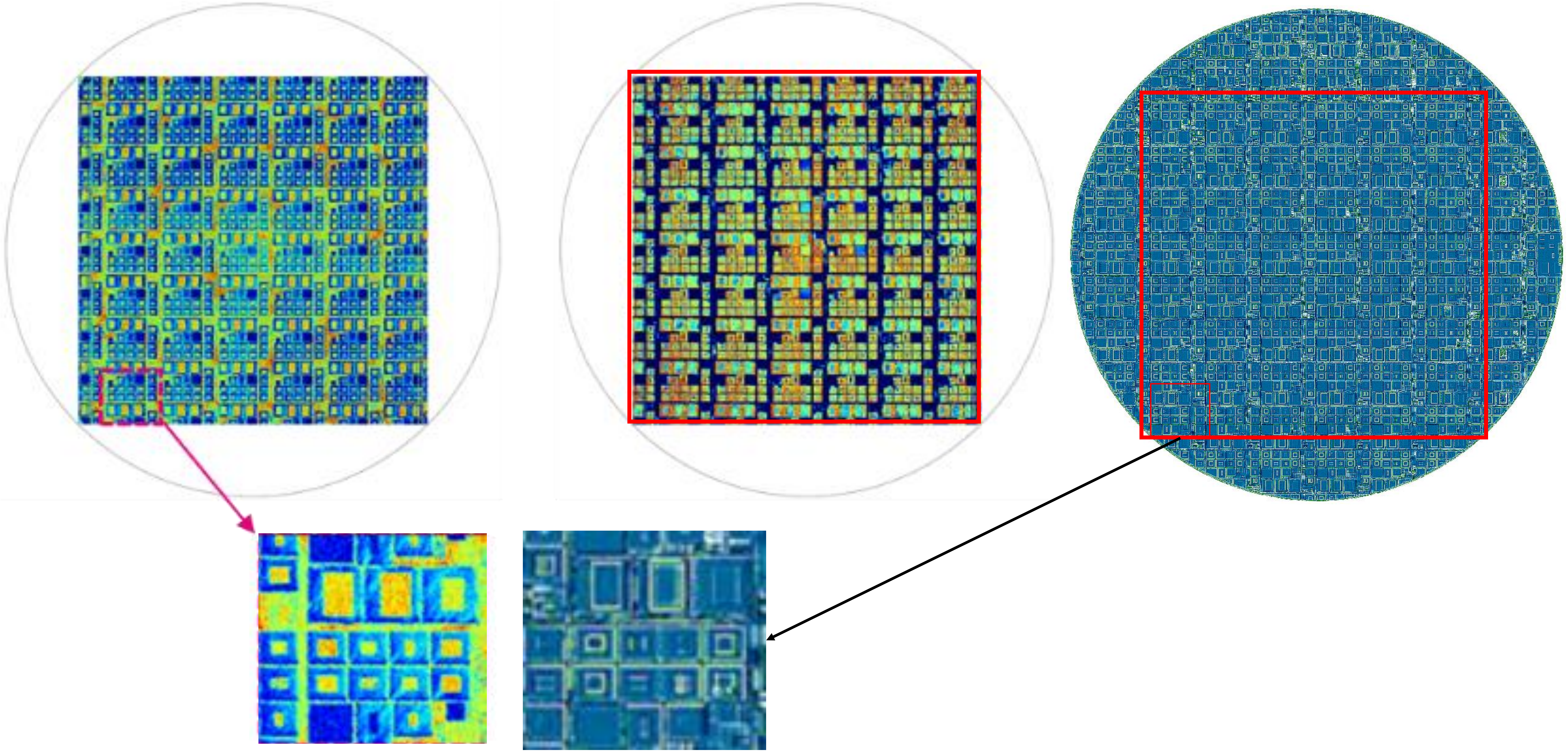
Interferometry

Imaging using Ellipsometry

- Local defects at the wafer scale

Ellipsometry imaging

Interferometry imaging



Imaging using Ellipsometry

- Ellipsometry is a very sensitive metrology technique
    - Sensitive to slight variations of the topography
    - Sensitive to slight variations of the optical properties
- Imaging Ellipsometry is capable of detecting slight defects
- Used as an imaging system: can supply to metrology and defectivity departments sensitive images to monitor process deviations

- But yet, low throughput due to the raster scanning

Future collaboration with a metrology supplier for the development of a new system

Knowhow transfer possible

Scatterometry modeling
→ Go faster

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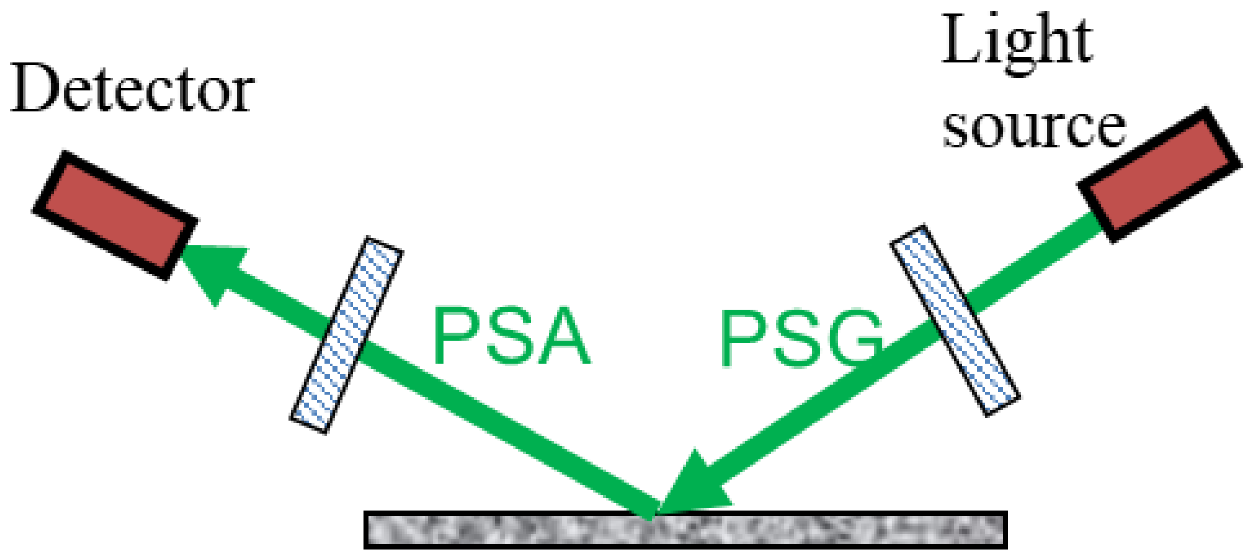
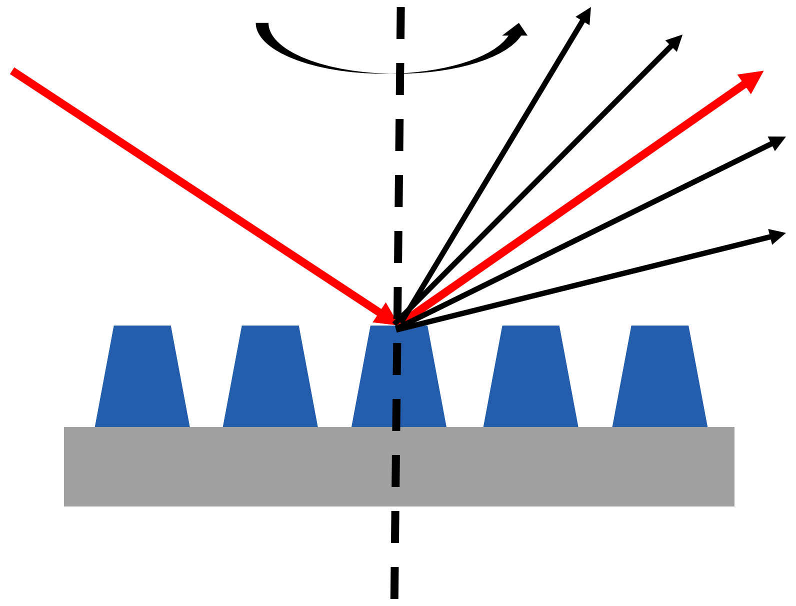
Scatterometry

- Scatterometry allows to reconstruct patterns shape
  - Classical ellipsometry or Mueller ellipsometer

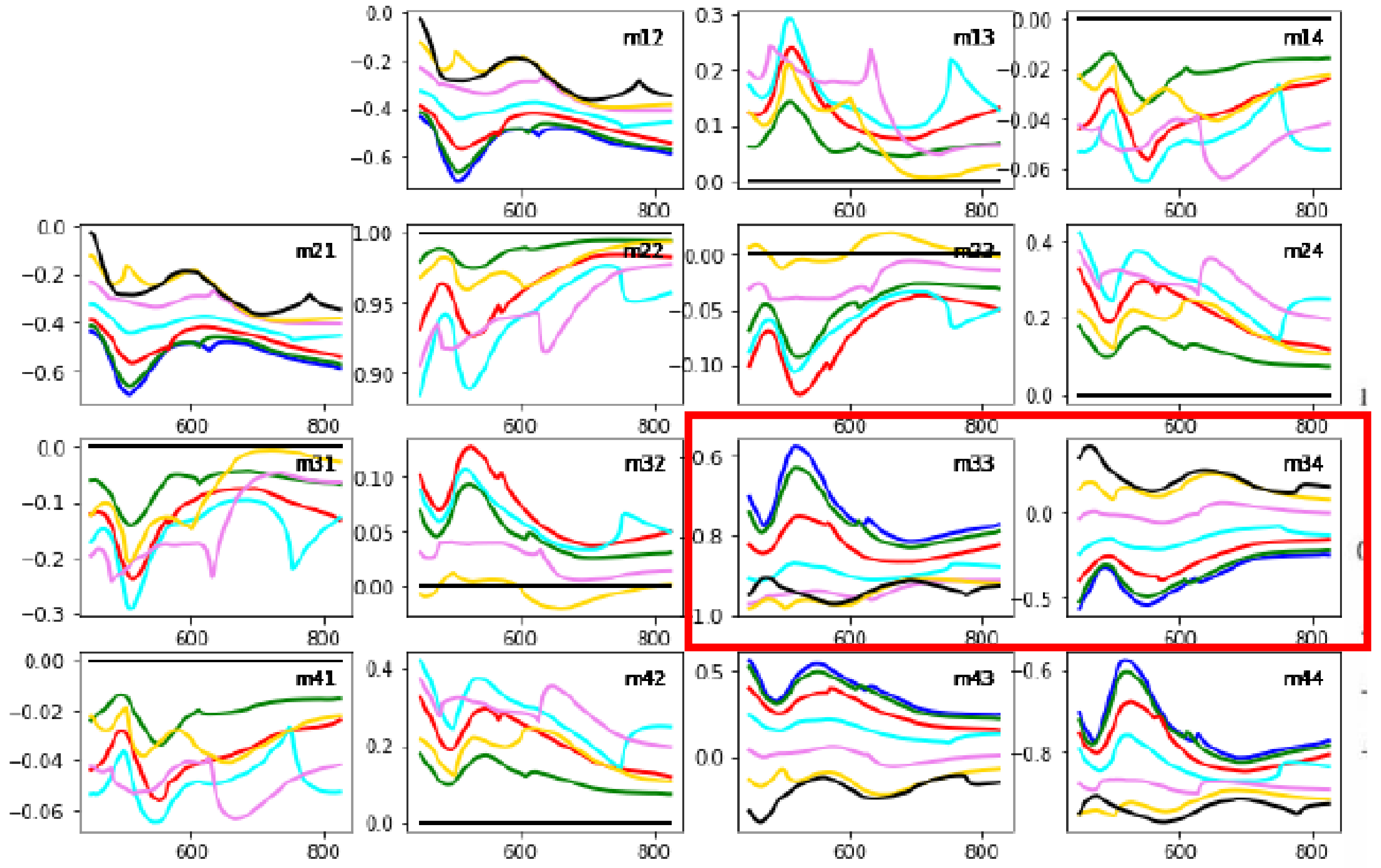
$$\begin{bmatrix} 1 & m_{12} & m_{13} & m_{14} \\ m_{21} & m_{22} & m_{23} & m_{24} \\ m_{31} & m_{32} & \boxed{m_{33}} & \boxed{m_{34}} \\ m_{41} & m_{42} & m_{43} & m_{44} \end{bmatrix}$$



  - Gratings are needed, field of the grating bigger than the spot size
- Modeling of a scatterometry signature



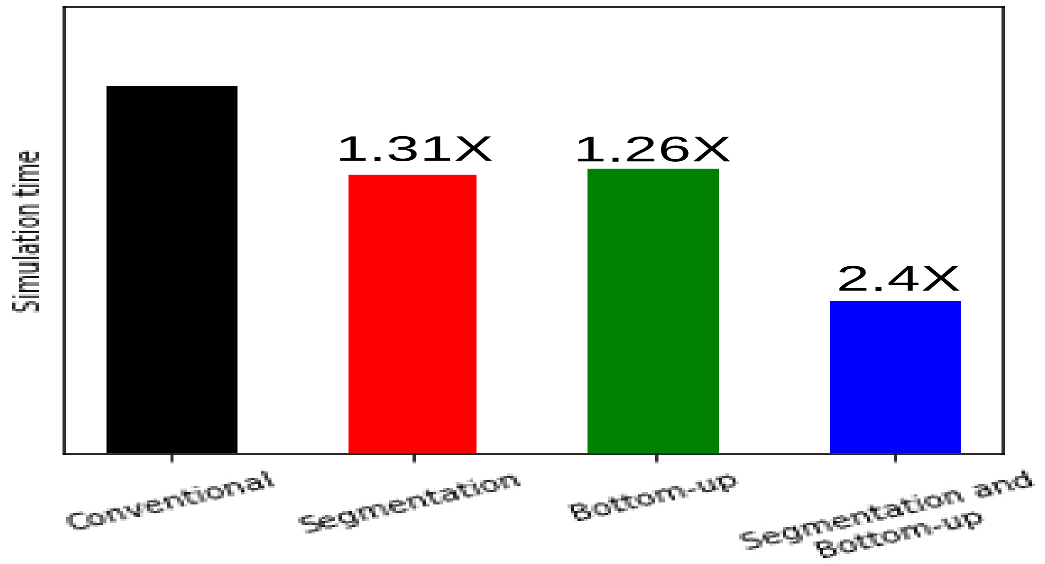
Modeling

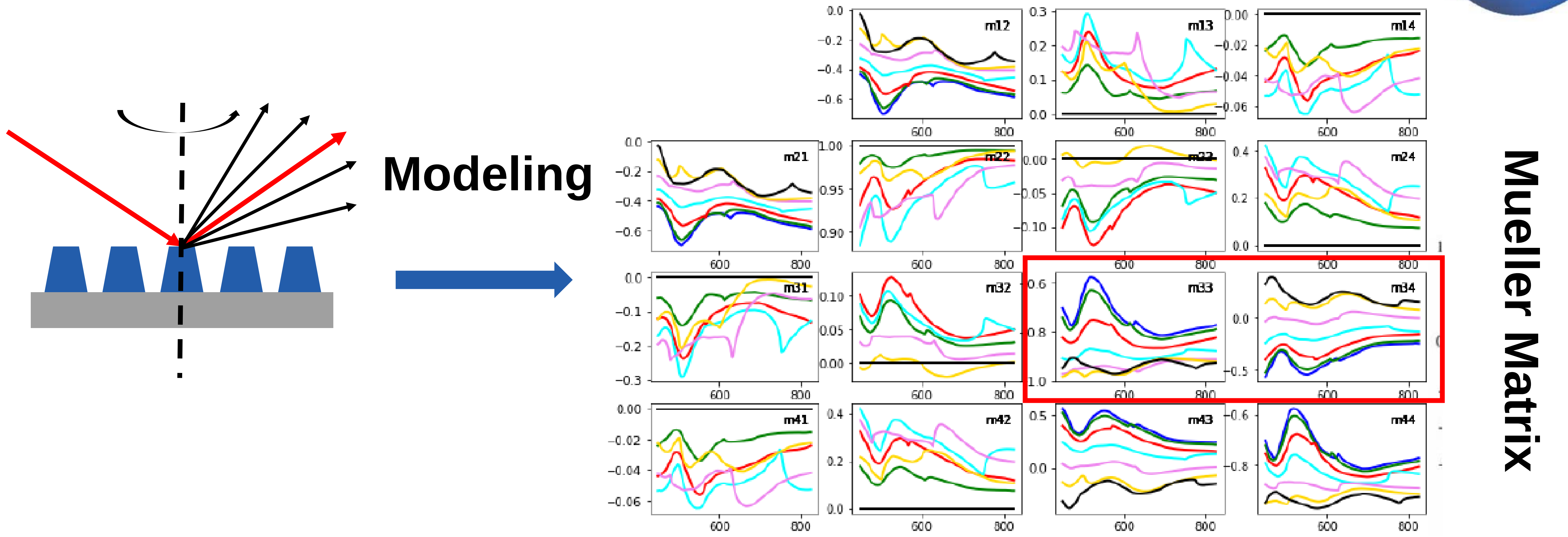


Mueller Matrix

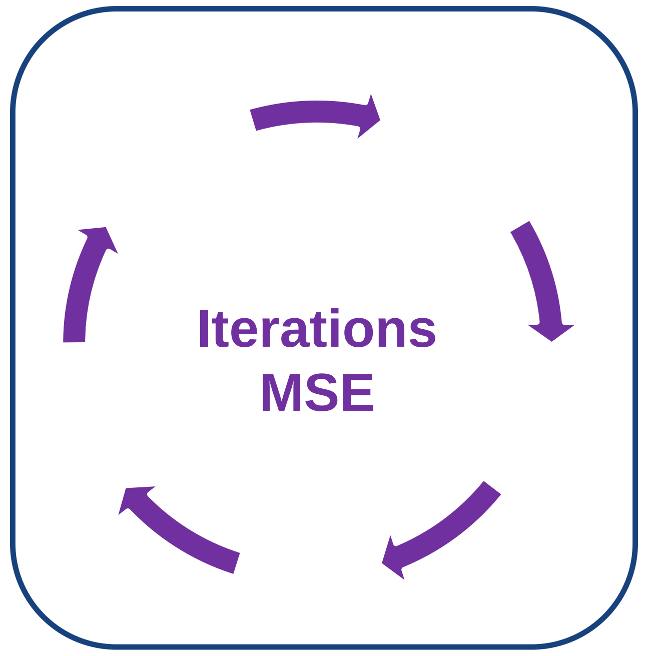
Scatterometry Modeling

- Known patterns shape ➔ Mueller matrix modeling
  - Time consuming
  - After optimization strategies:



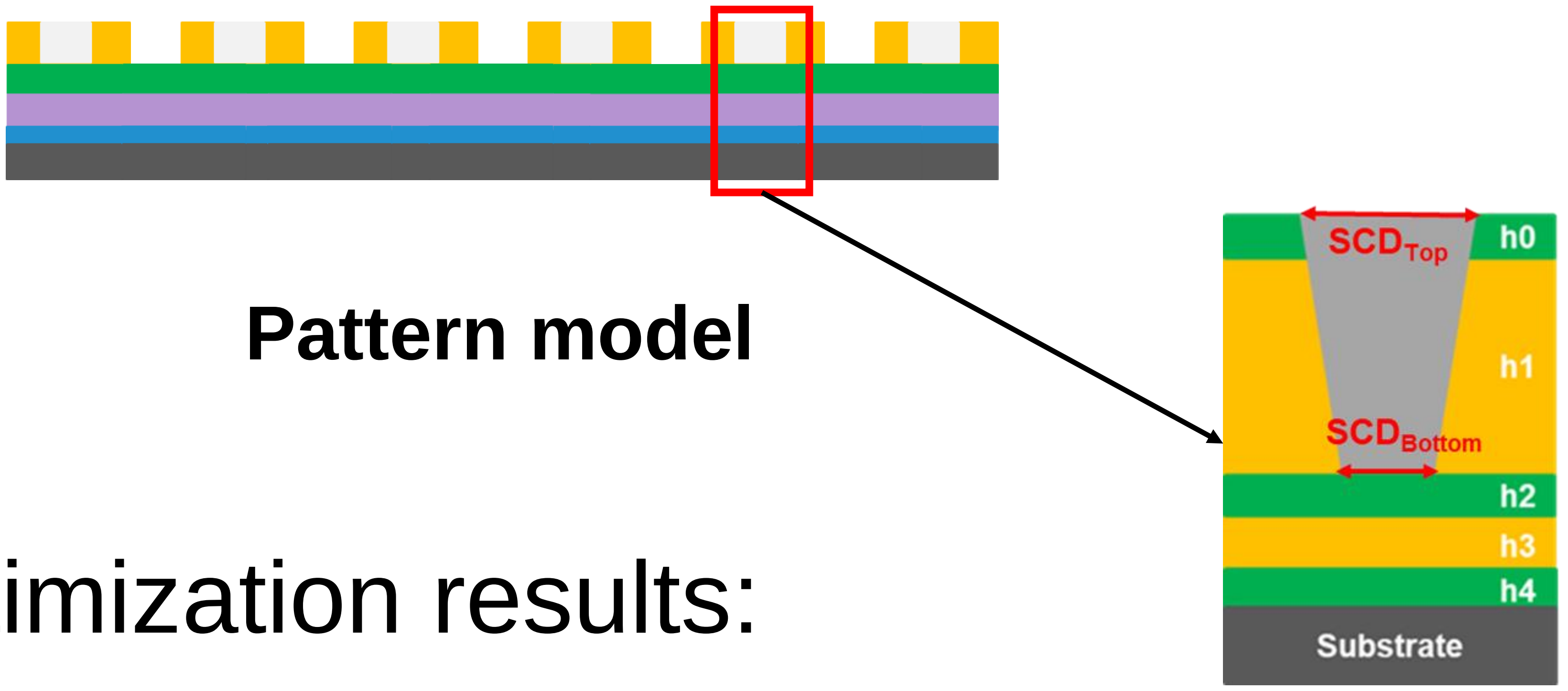


- Unknown Pattern shape reconstruction ➔ Minimization of the error
  - Multiple iterations than minimize the Mean Square Error
  - Number of iteration > 50
  - Extremely long computation times

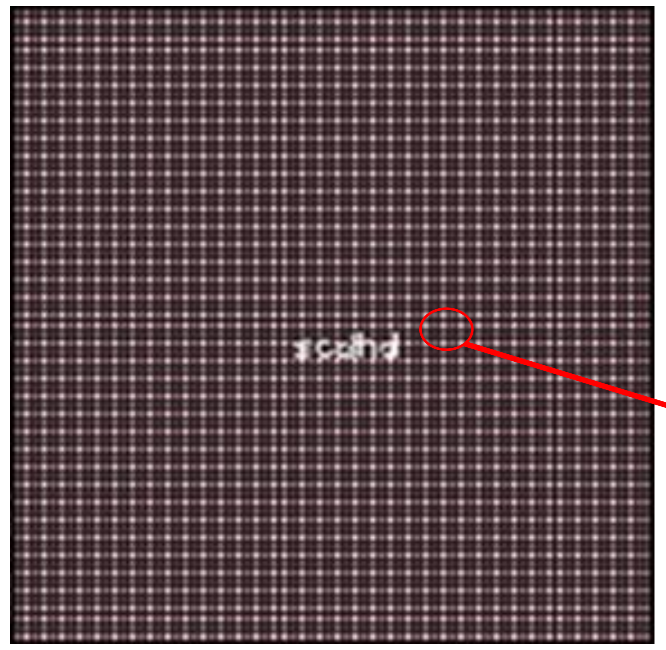


Scatterometry Modeling

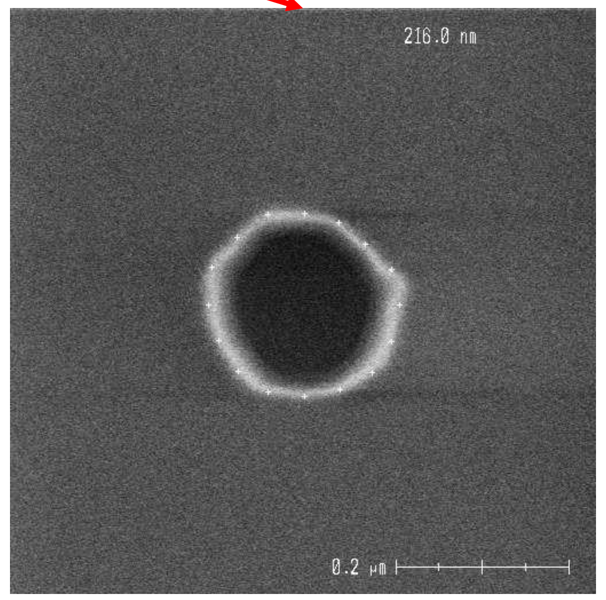
- Use case: Optical diffusive patterns
  - Metrology dies: Array of holes



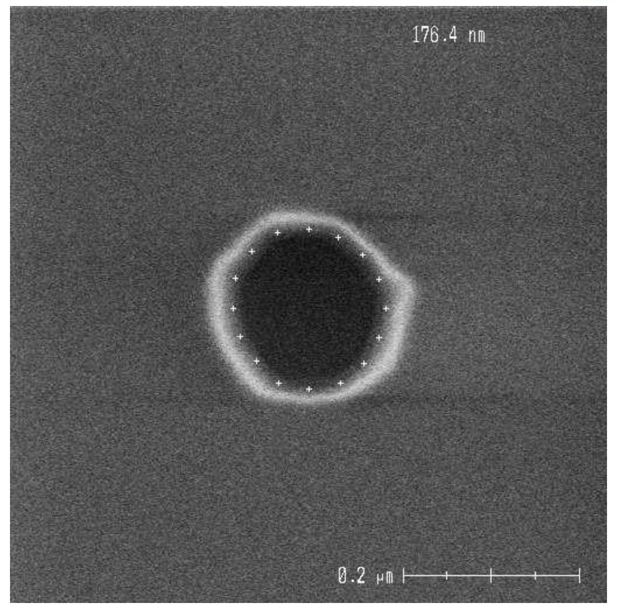
Pattern model



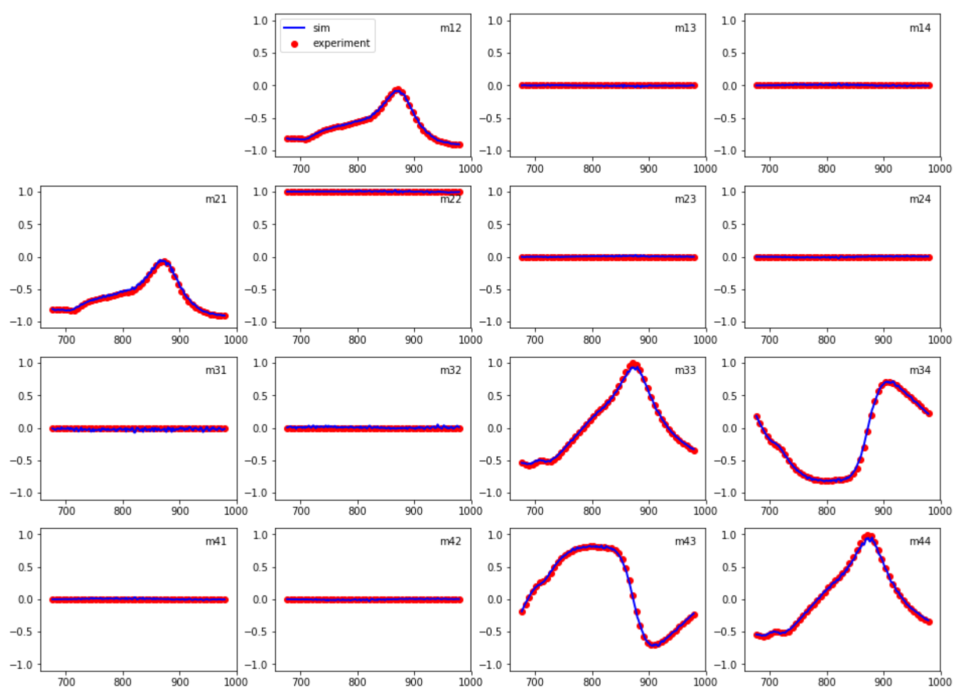
SEM metrology die



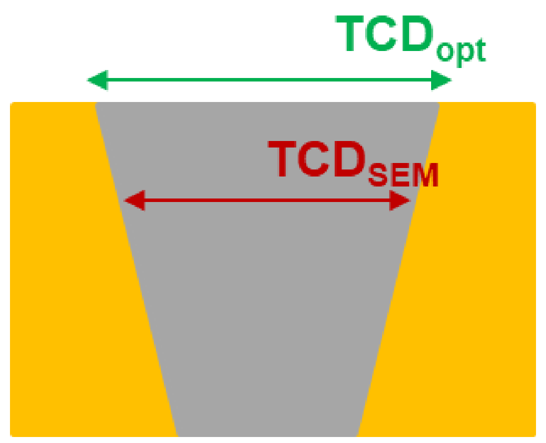
CD$_{SEM}$ Top



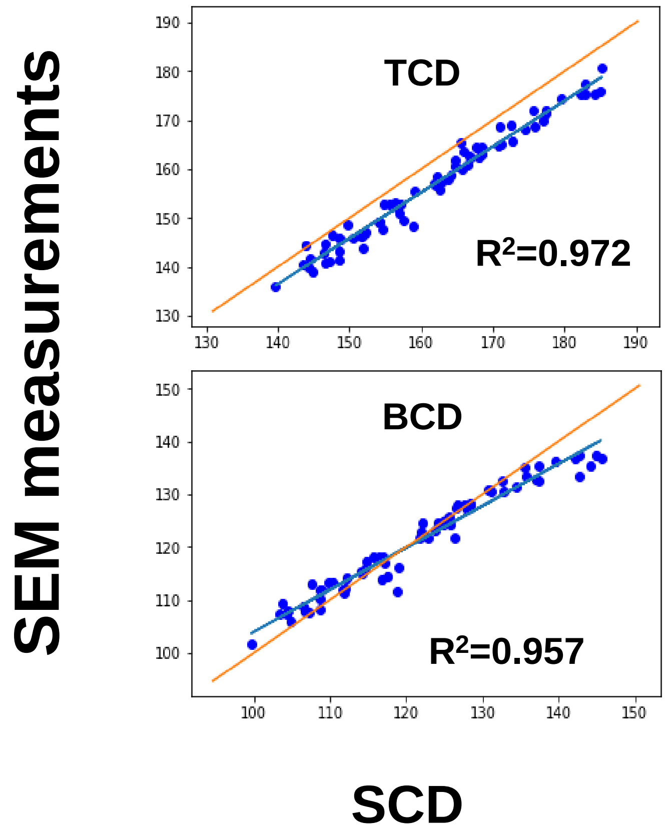
CD$_{SEM}$ Bottom



- Optimization results:



SEM: TCD$_{SEM}$ ≤ TCD$_{opt}$



Parameters	Mean (nm)	99.99% CI (nm)
$\lvert$TCD-offset TCD$_{SEM}\rvert$	1.7	1-2.4
$\lvert$BCD-offset -BCD$_{SEM}\rvert$	2.6	1.4-3.7
h0	48.94	48.65-49.23
h1$_{eq}$	652.23	648.66-655.8
h2	44.73	43.98-45.48
h3	74.6	74.1-75.09
h4	24.22	23.38-25.05

Method	Time magnitude
Conventional optimization	days
+ Two technique: Bottom up and Segmentation	hours
+ Resolution	minutes
+ Optimization with analytical gradient of thickness	minutes
+ Equivalent layer	seconds

Scatterometry @ LTM

- Scatterometry code developed ➔ handles Mueller scatterometer signatures
- Conical code ➔ 3D patterns modelled
- Thanks to optimized strategies:
  - Time computation drastically reduced ➔ from weeks to seconds

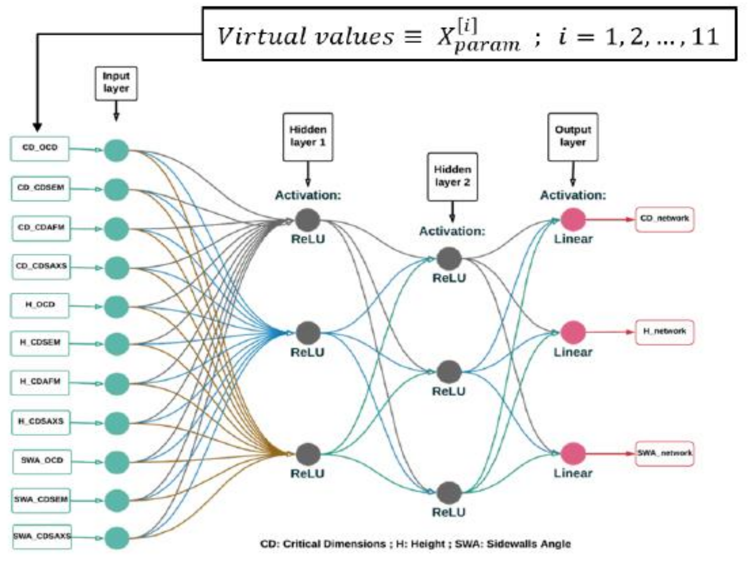
Address Booster 2 : Go faster of MadeIn4

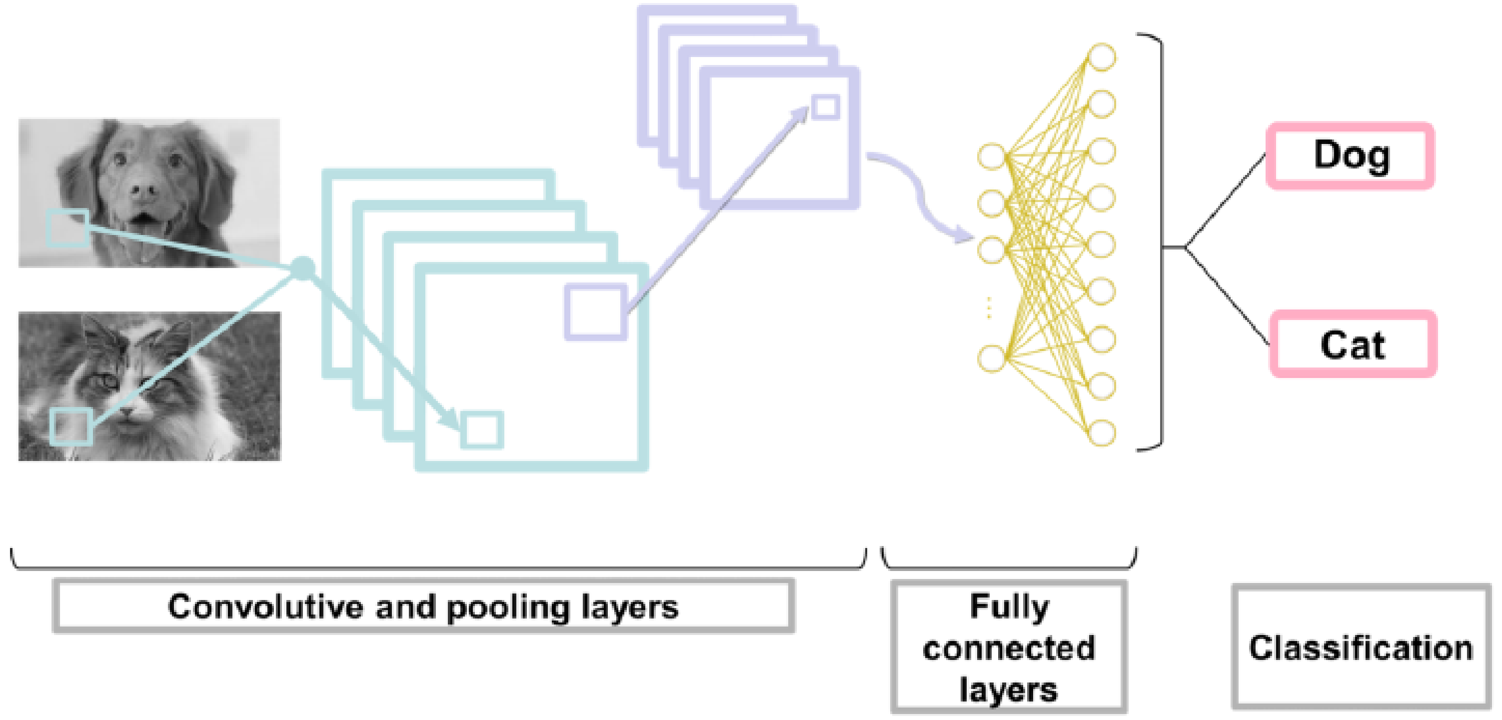
Machine learning and deep learning ➔ Go Faster

Artificial Intelligence algorithms

Computation time: AI algorithms are very efficient **once trained**

- Neural Network
  - Principle
- Convolutional Neuronal Network (CNN)
  - Principle : Automatically choses the proper features in an image
  - Training : Numerous Labelled images or data are used to set the features needed
  - Typical use case : Classification of images
    - Predict if an image belongs to a given class
- Regional Convolutional Neural Network (RCNN)
  - Principle : Automatically detects a class in an image and localize it in the image
  - Typical use case : Detection of object
    - Predict various localization of objects in an image



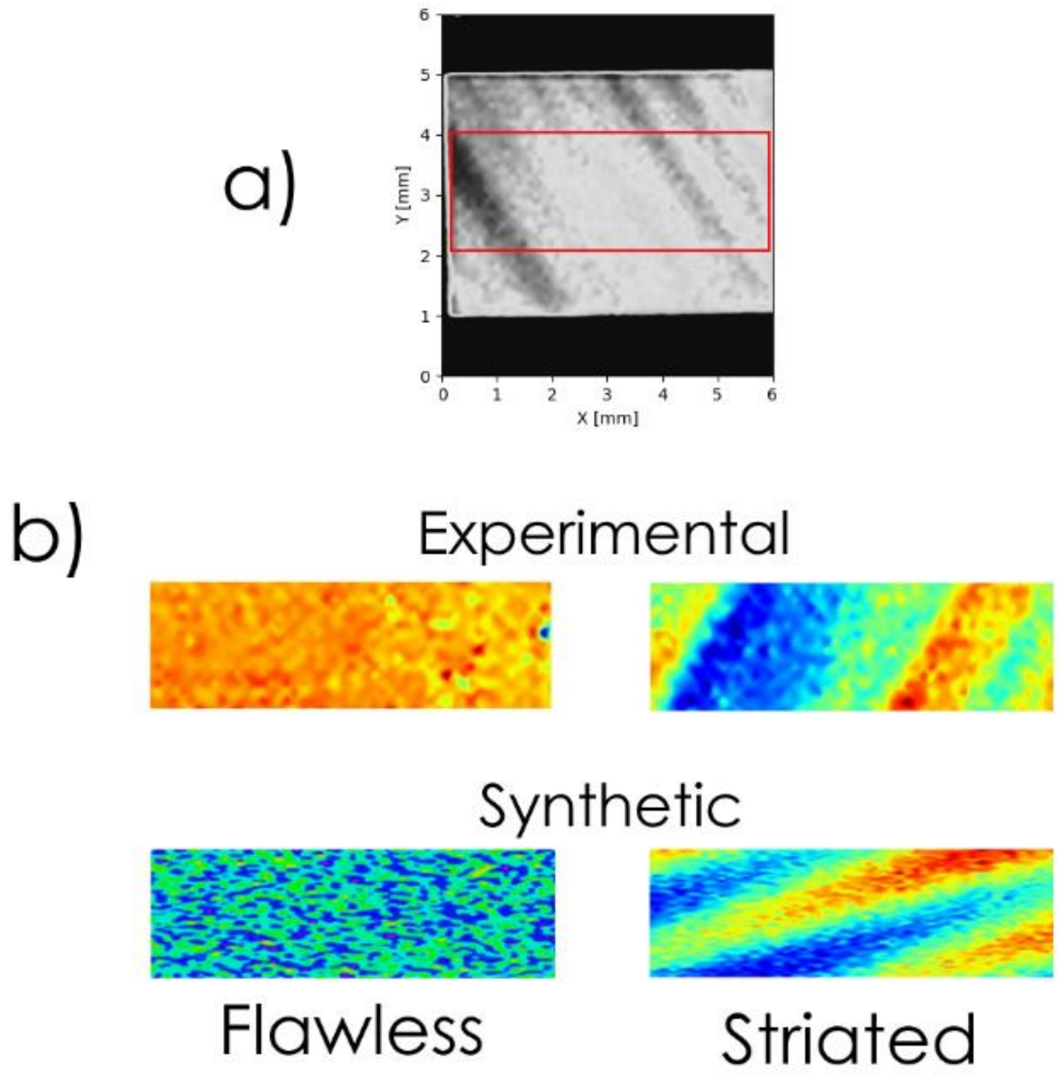


All these algorithms need to be trained using relevant images or data

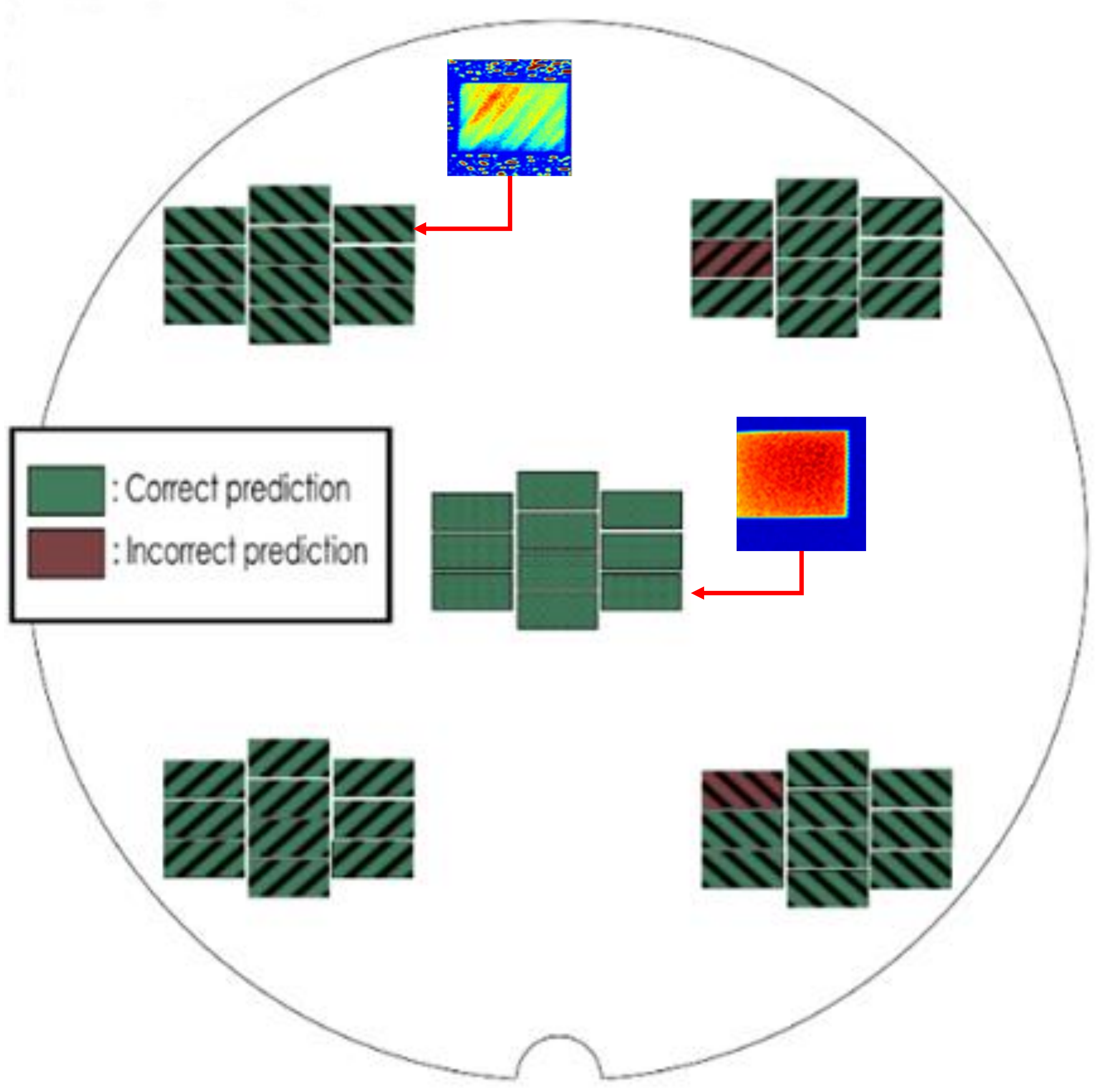
Rapid defects detection in images with AI

Striation detection: At the center of the imaging die

- Training set of data:
  - Only synthetic ones: 200



Ellipsometry imaging



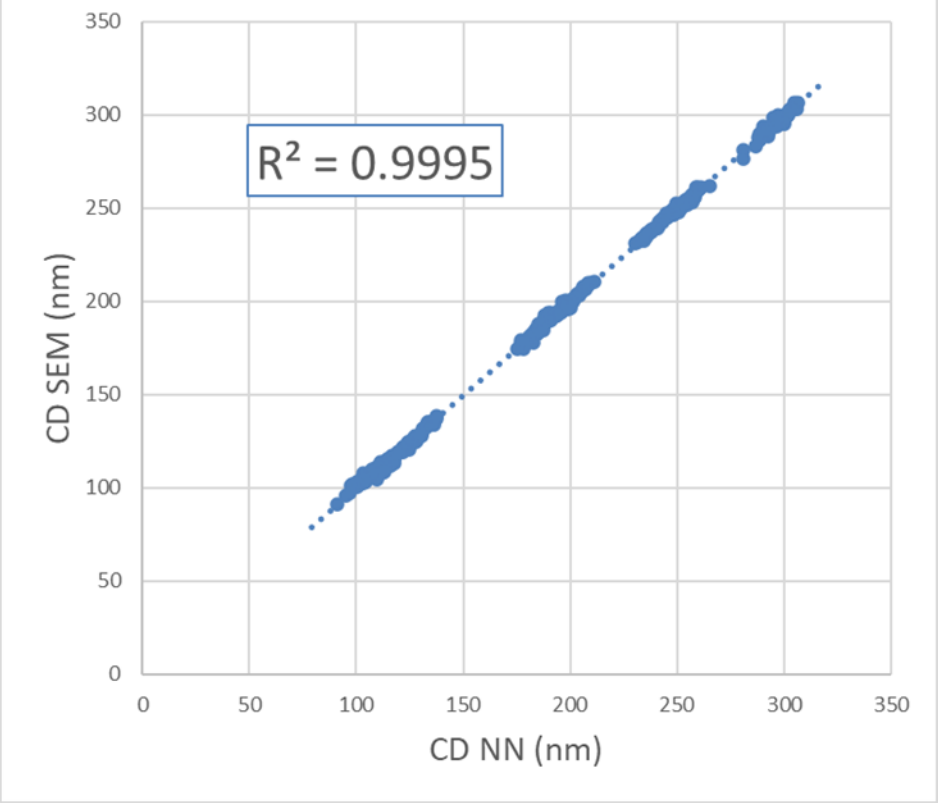
96% detection success

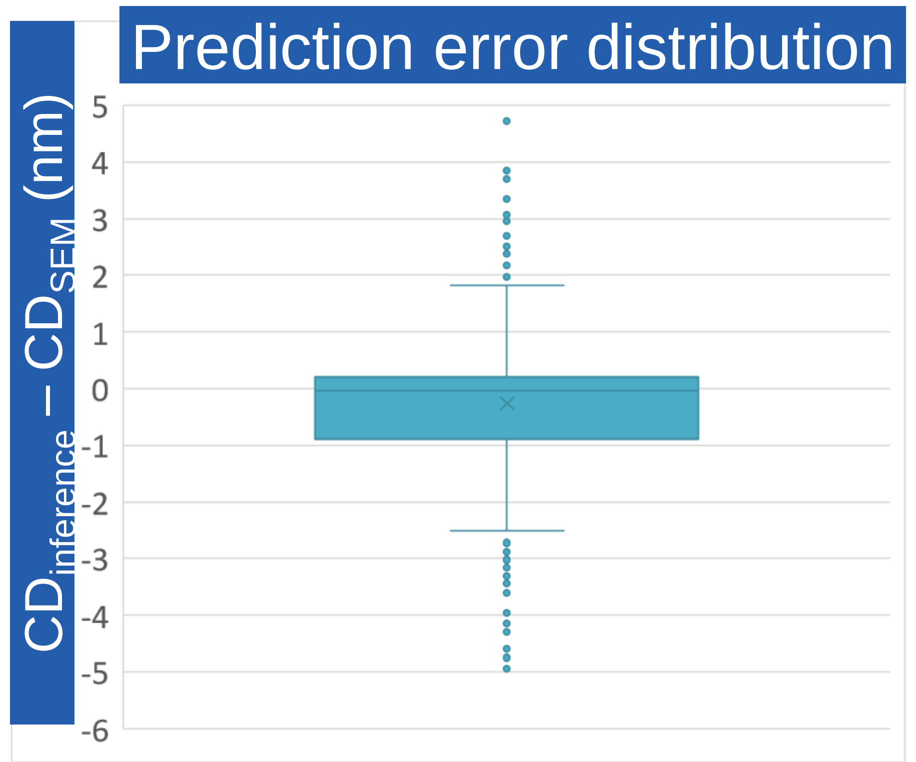
CNN and metrology

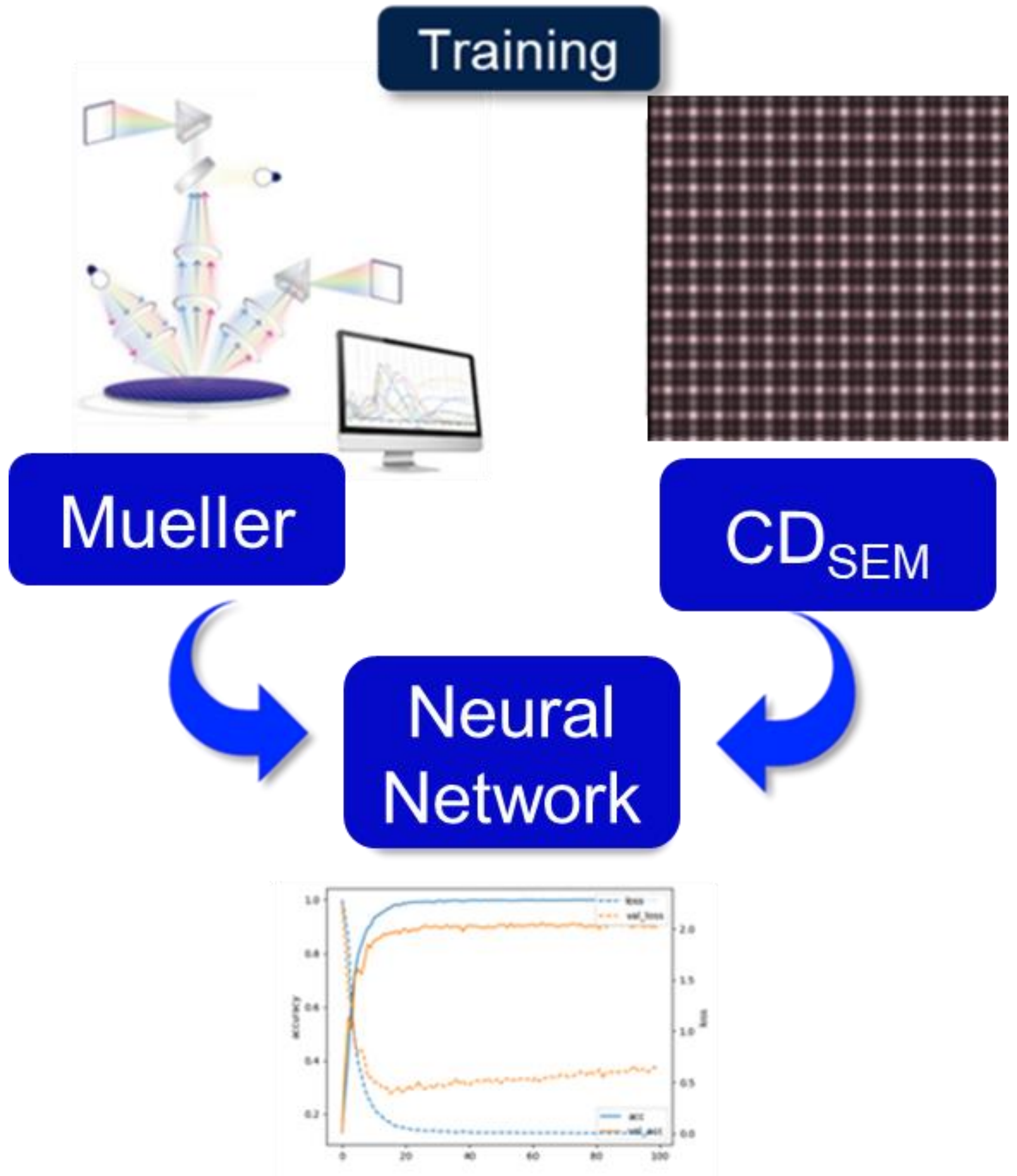
NN training using Scatterometry Signature

$$\begin{bmatrix} 1 & m_{01} & m_{02} & m_{03} \\ m_{10} & m_{11} & m_{12} & m_{13} \\ m_{20} & m_{21} & m_{22} & m_{23} \\ m_{30} & m_{31} & m_{32} & m_{33} \end{bmatrix}$$

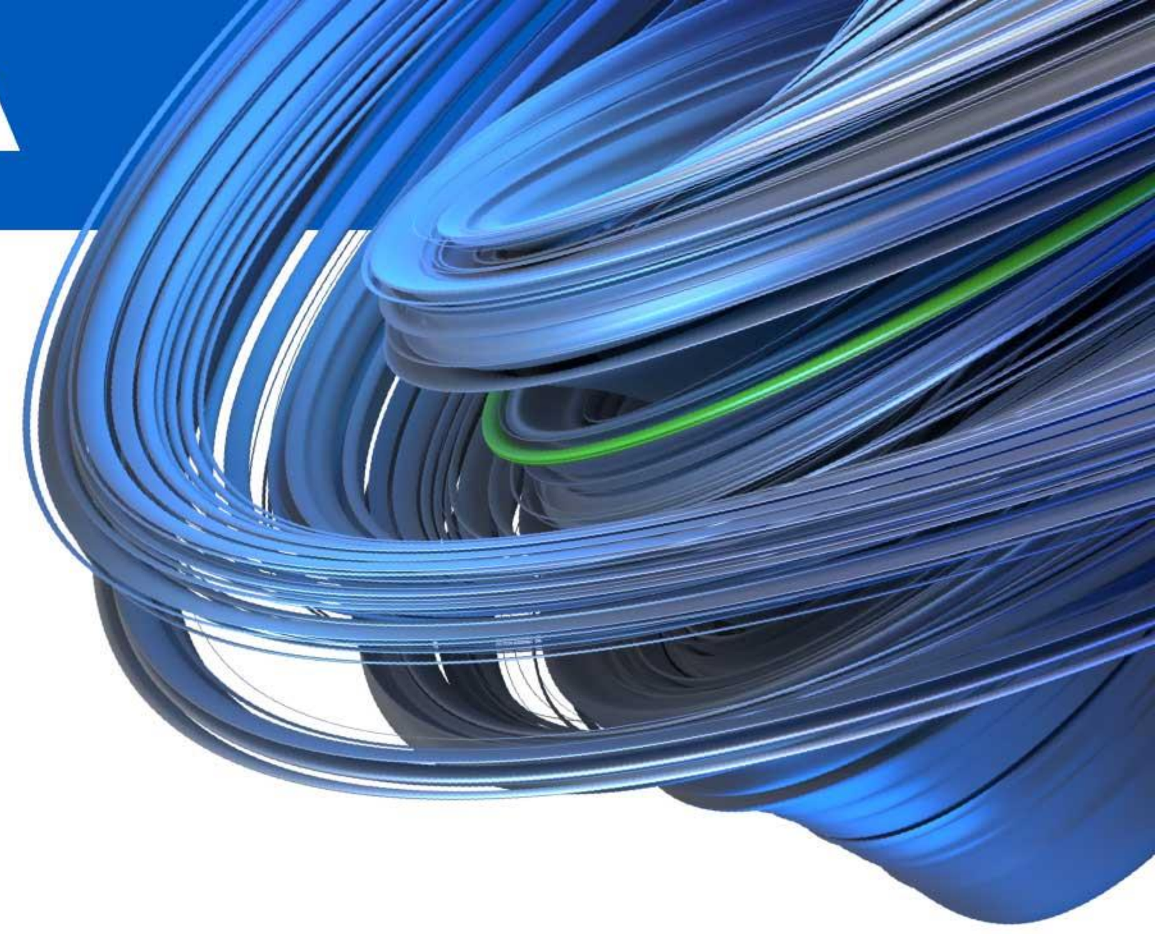
- Use case: Optical diffusive patterns
  - **Only experimental data**
    - Mueller Matrix measured at ST ➔ Twelve elements $M_{i,j}$ stacked all together
    - CD measured by SEM at ST ➔ Two CD_{SEM} per metrology die (Top and bottom)
  - Training/test/validation Set: **440** stacked Mueller elements and CD_{SEM}
- Prediction (inference) of a measured CD







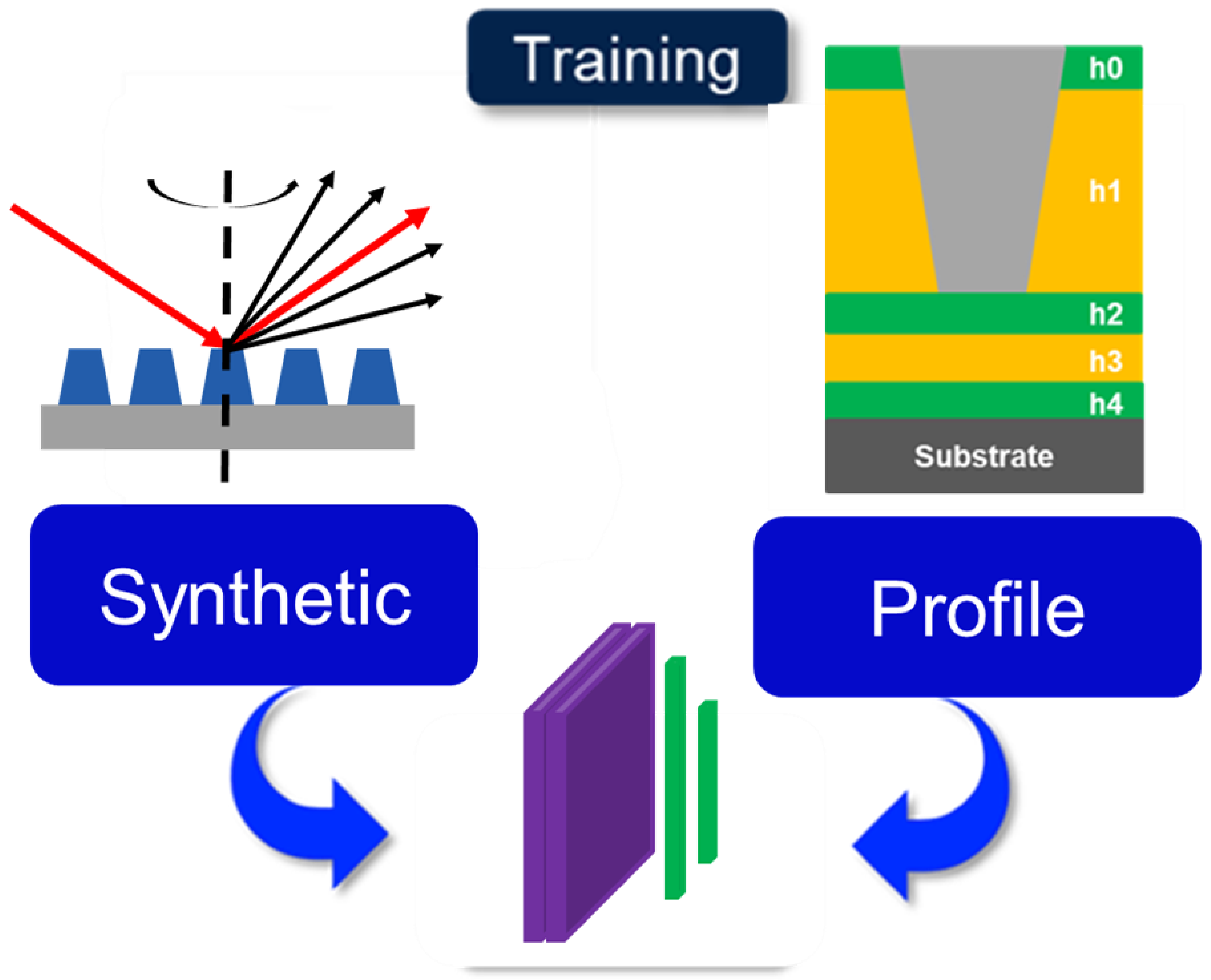
Excellent prediction but beware overfitting!

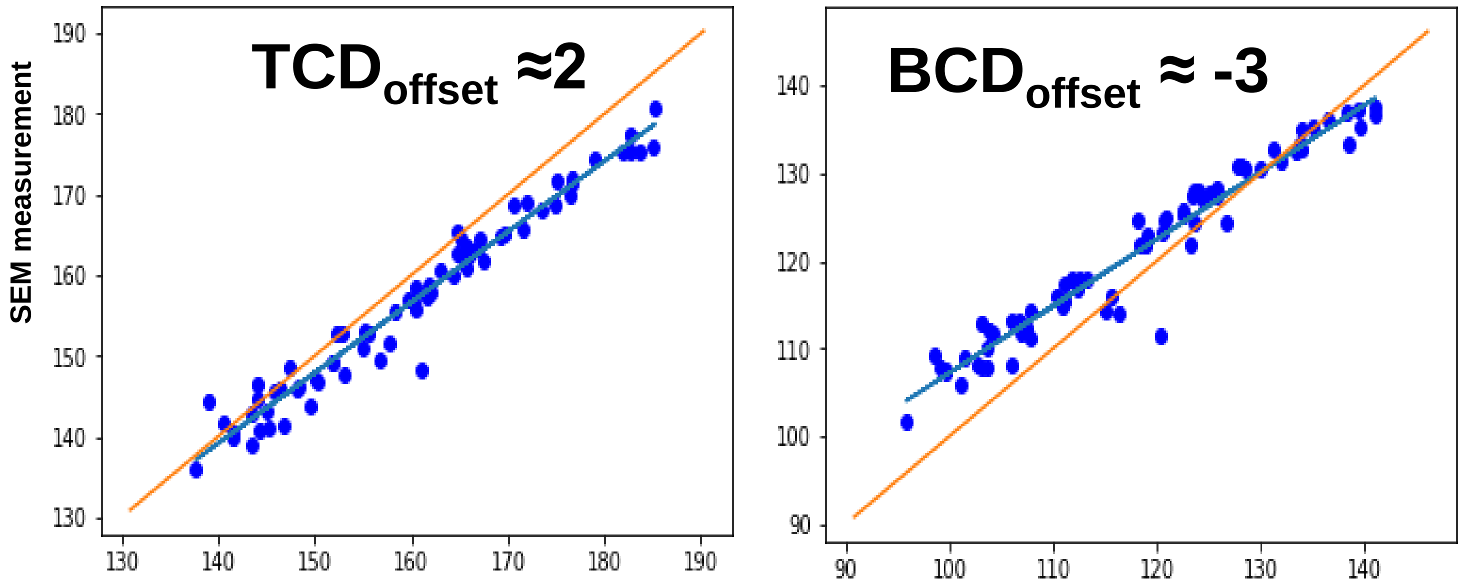


CNN and metrology

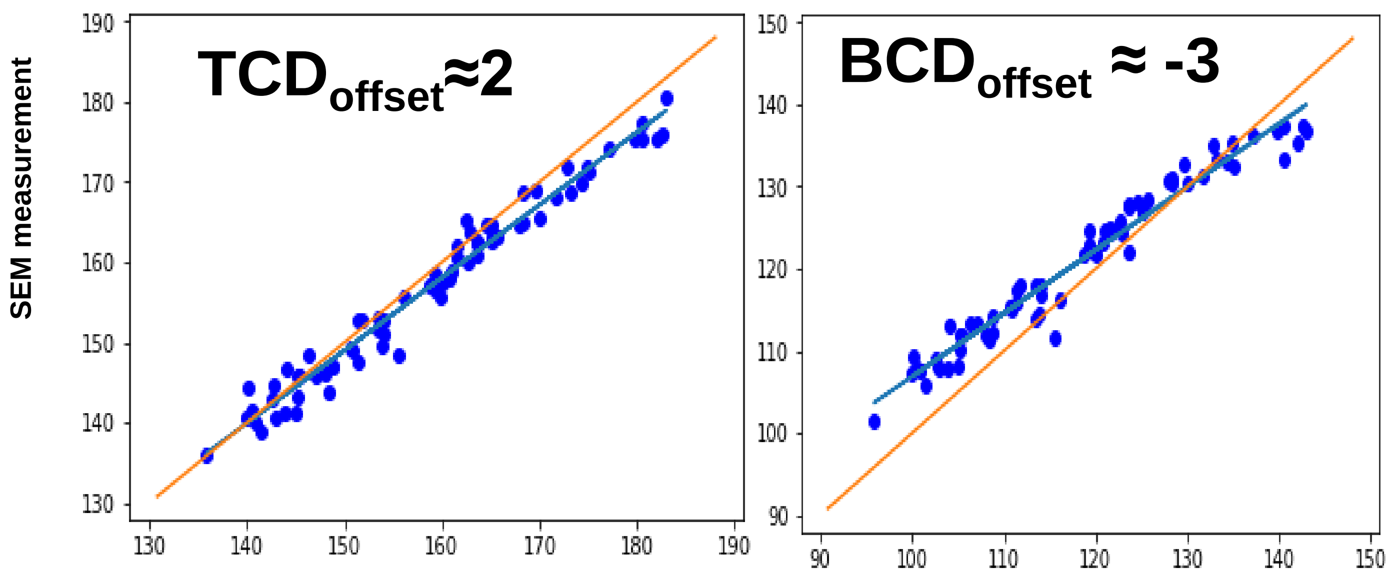
CNN training using Scatterometry Signature

- Use case: Optical diffusive patterns
  - **Only synthetic data**
    - Mueller Matrix simulated➔ 3 most sensitive elements $M_{1,2}$, $M_{3,3}$, $M_{3,4}$, stacked
    - 7 simulated Metrix ➔ Top CD, Bottom CD, five layers thicknesses h_i
  - Massive training Set: 4 mn to generate thanks to LTM optimization code (weeks else…)
  - CNN architecture: one convolutional layer, 2 fully connected layers
  - Training (60%)/test (20%)/validation (20%) Set: **45 000** stacked Mueller elements (≈1h)
- Prediction of Top and bottom CD from experimental data and comparison with CD_{SEM}



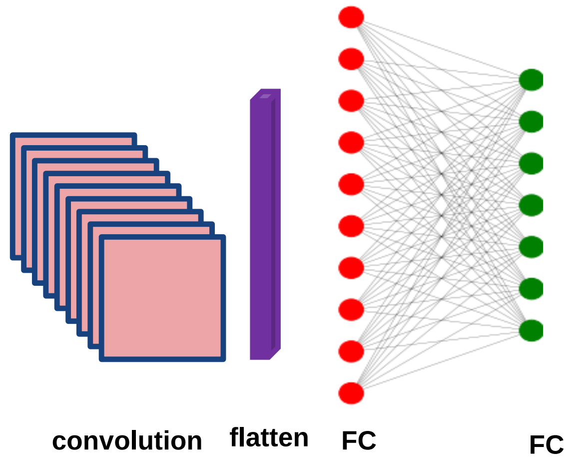


CNN prediction (2-3 s)



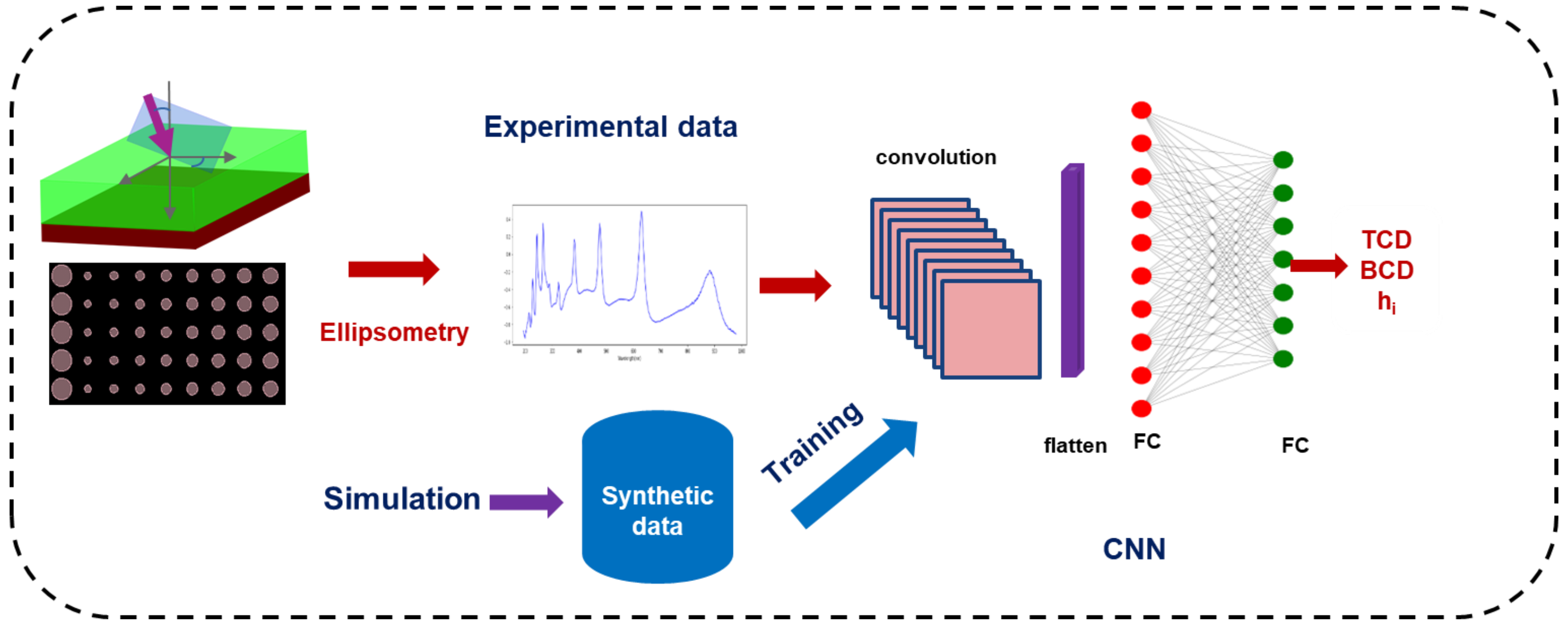
LTM Optimized rigorous optimization (2 hour)

Same accuracy as optimization
BUT
faster!

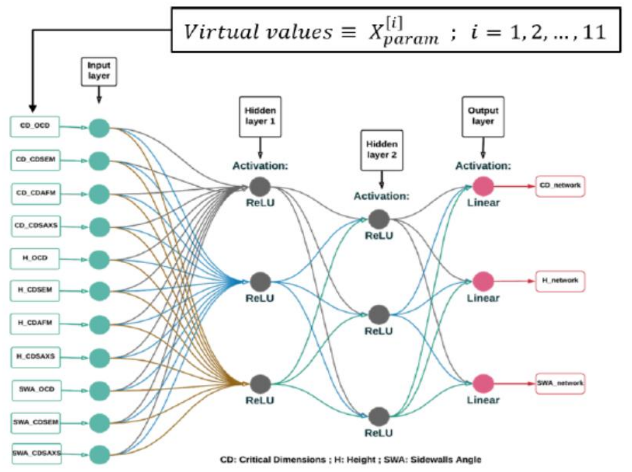


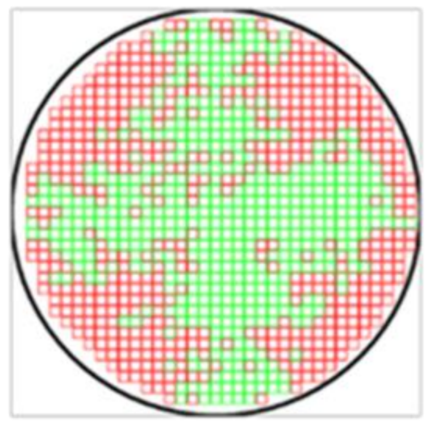
Artificial Intelligence @ LTM

- Metrology @ LTM
  - Reduces drastically the computation time
    - **3D** scatterometry : complex non linear models

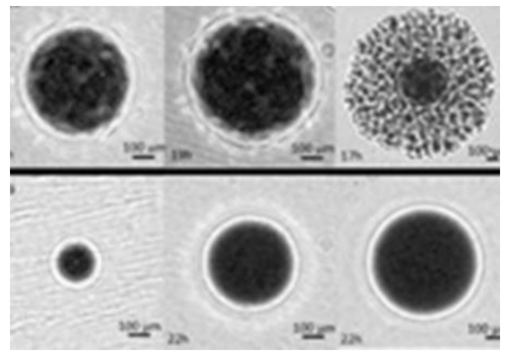


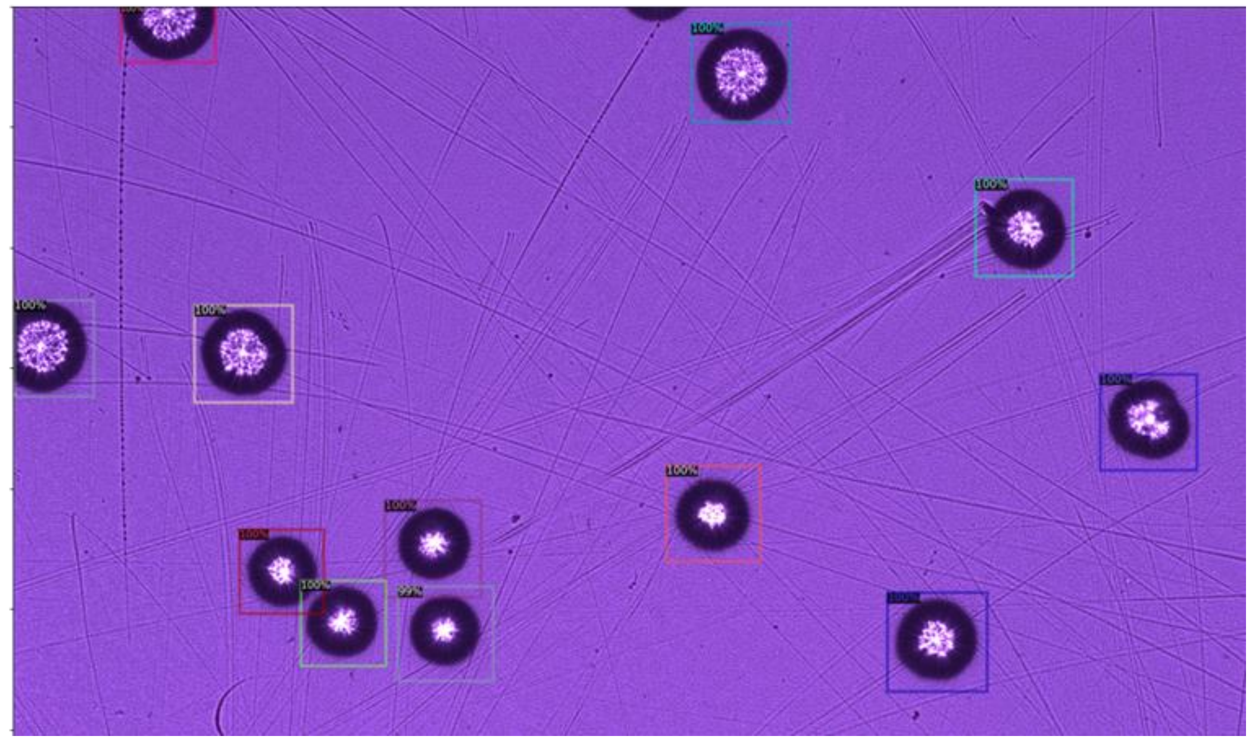
  - Simplify **hybridization** of metrology tools
    - Different data dimensions/formalisms, different models
      - Hard to compute rigorously
    - With NN, all data are handled





- Object detection @ LTM
  - Automatic detection of defect in images by CNN, RCNN for microelectronics
    - At the frontier between Metrology and defectivity
  - Detection of bacteria colonies for Health applications:





Conclusions and perspectives

- Imaging using Ellipsometry sensitive to detect defects
  - Aberration corrections in images
  - Resolutions sufficiently high for defect detections

- Scatterometry codes highly optimized ➔ Computation time decreased
  - From hours to seconds for one simulation
  - From weeks to minutes for optimization

- Machine learning and deep learning strategies successfully predicts:
  - Defects on dies or wafers
  - Metrics for complex 3D structures

TRL 3-4 achieved

New partnership with metrology suppliers/ microelectronic industry to move to TRL 5

Thank You