MACHINE LEARNING APPLICATION FOR METROLOGY AND PROCESS CONTROL

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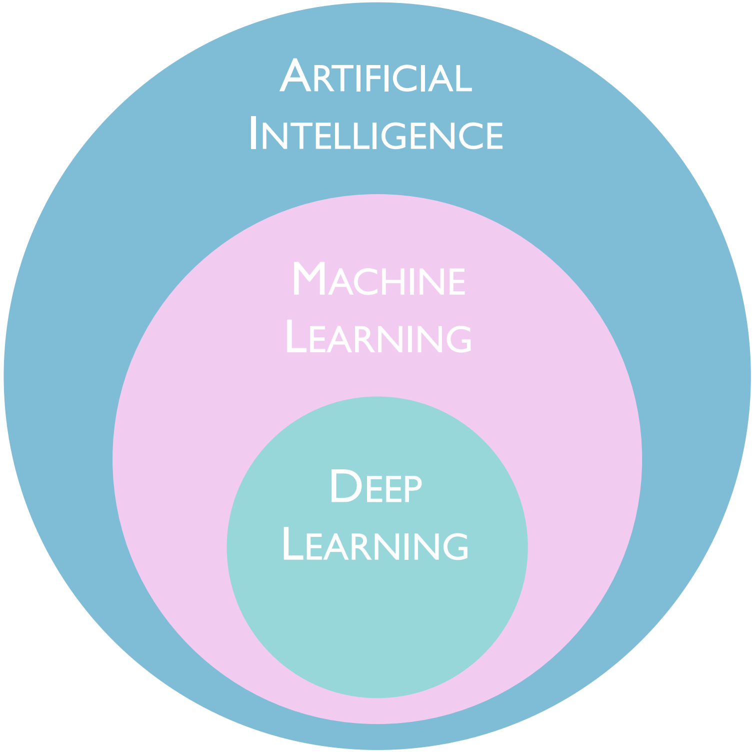
MACHINE INTELLIGENCE



- Reasoning
- Generic Goals
- Concept Building
- Language Building
- Pattern Recognition
- …

Tuning model parameters based on available data = "learning"

- Pattern Recognition
- Feature Extraction
- …

Using neural networks as machine learning model

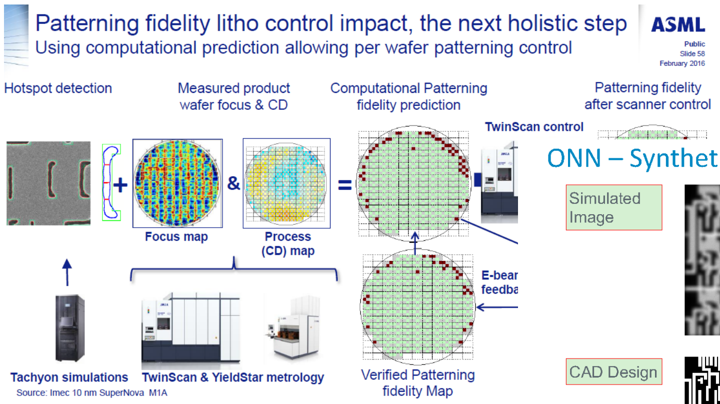
- Multilayer Perceptron
- Convolutional Neural Networks (CNN)
- Long Short Term Memory (LSTM)
- …

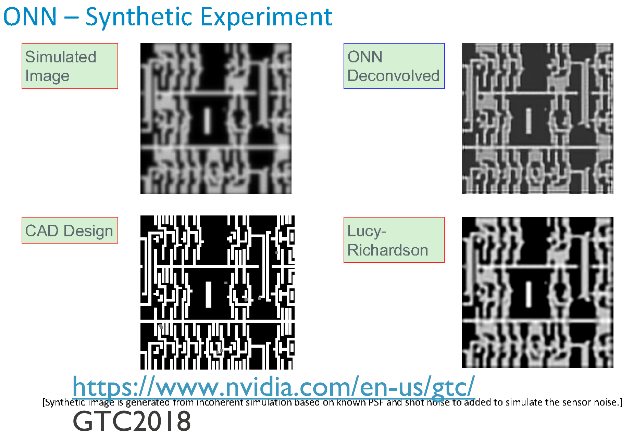
Machine Learning is a subset of general Artificial Intelligence

Deep Learning is a technique to do Machine Learning

THIS IS HAPPENING IN OUR INDUSTRY

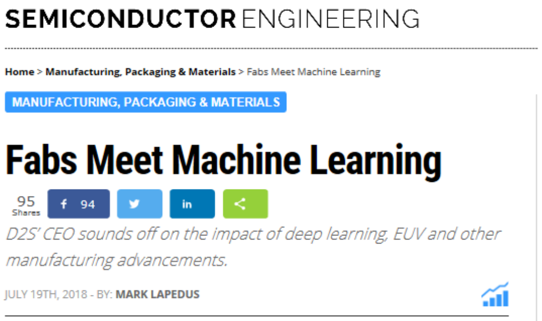
SOFTWARE INCLUSIVE OF SIMULATION/EMULATION





https://www.nvidia.com/en-us/gtc/

GTC2018



SE: Is deep learning being used in semiconductor manufacturing?
Fujimura D2S CEO: It's happening fast, but it's in the beginning stages. I don't think there is any question that deep learning is already impacting the semiconductor manufacturing sector.

KLA-Tencor

In his presentation, **Applied Materials** president and CEO Gary Dickerson will explain how the rapid increase in data generation, combined with A.I. and machine learning, creates the need for new system architectures and compute models in the years ahead.
https://www.globenewswire.com/news-release/2017/09/21/1126089/0/en/Applied-Materials-Focuses-on-Enabling-Artificial-Intelligence-Era-at-2017-Analyst-Day.html

MACHINE LEARNING ON METROLOGY DATA

Value

- Reduced Time Spent @ Metrology
- Improve yield

Reduced Time Spent @ Metrology

- Predict bad wafer → Stop early
- Predict Bad/Good Dies
  → Select the parts to be measured

Improve Yield

- Correct errors in later process steps

Feature Reduction

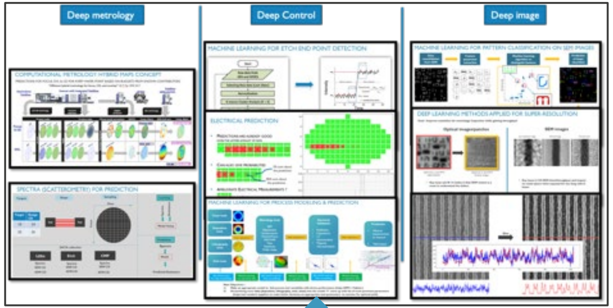
- Reduce the amount of data from metrology tools to be processed
- Reduce useless measurements

Data Analysis on Metrology Tools

- Assess metrology tool errors

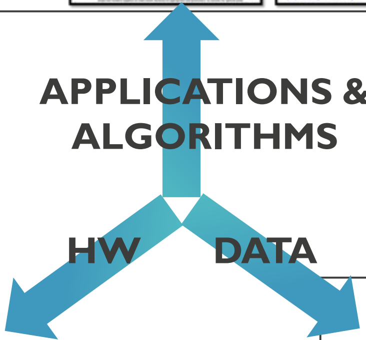
MACHINE LEARNING AT IMEC

ML applications: Deep metrology, deep control, deep image

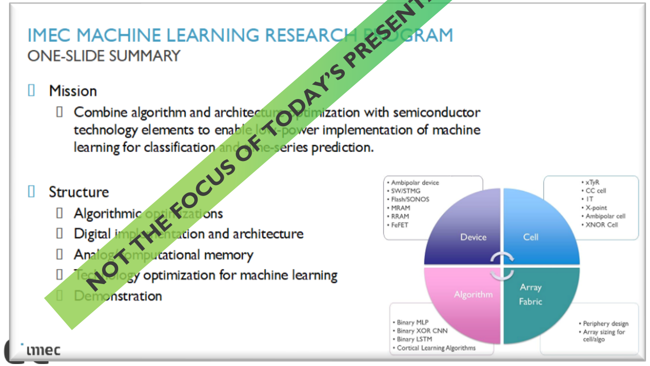


1. ML for sampling
2. ML for prediction
3. ML for process control
4. ML for tool maintenance
5. ML for image enhancement

6. ML to the next stage



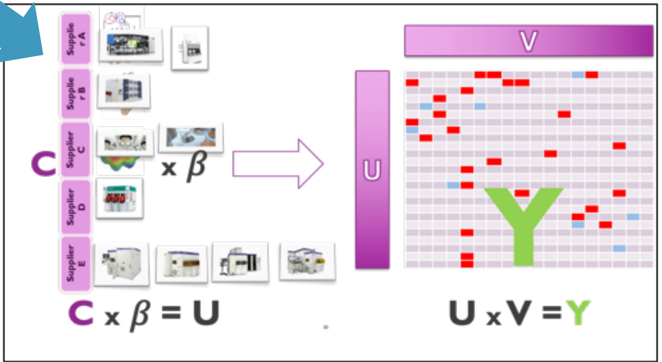
HW based ML



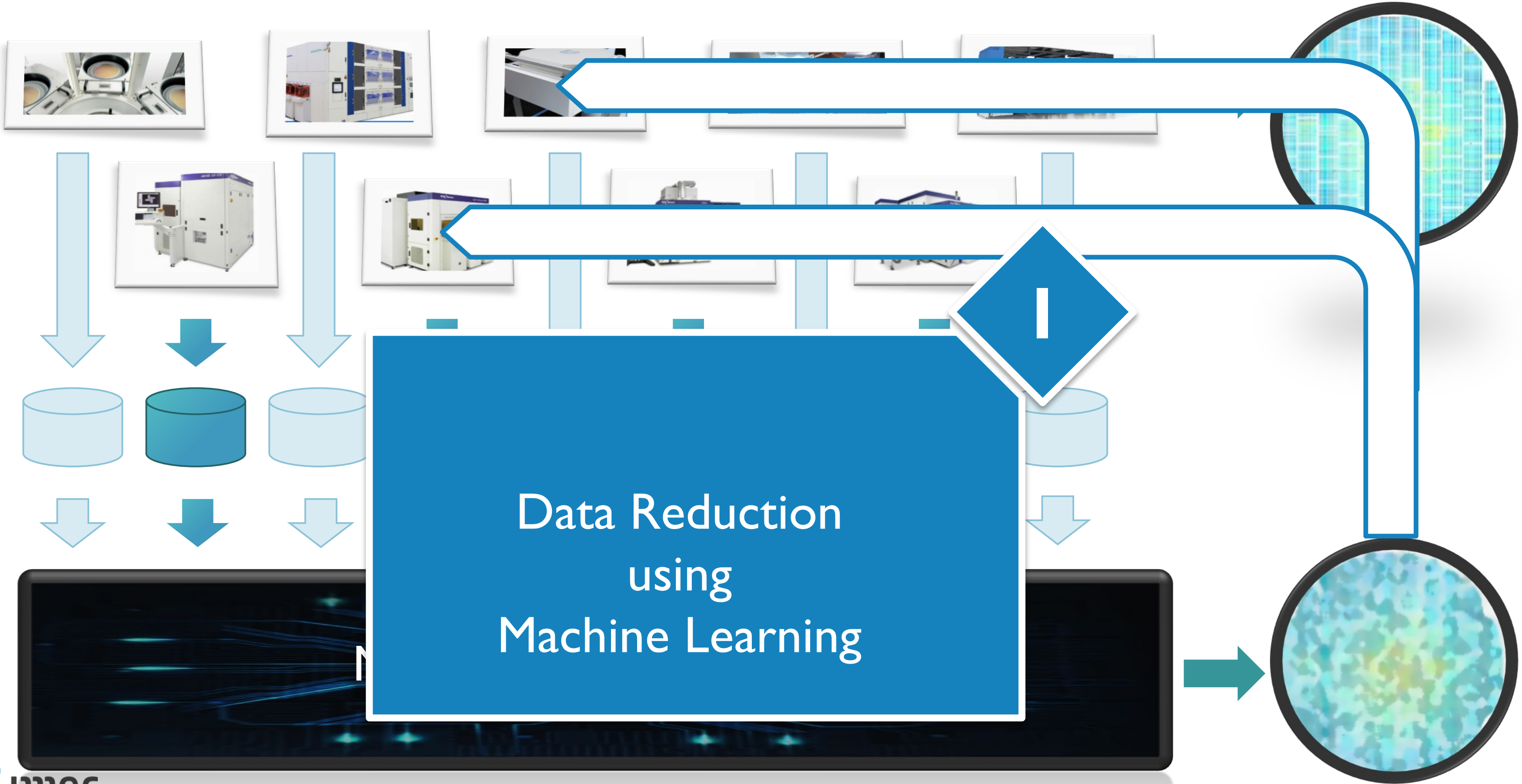
IMEC MACHINE LEARNING RESEARCH PROGRAM
ONE-SLIDE SUMMARY

- Mission
  - Combine algorithm and architecture optimization with semiconductor technology elements to enable low-power implementation of machine learning for classification and time-series prediction.
- Structure
  - Algorithmic optimizations
  - Digital implementation and architecture
  - Analog computational memory
  - Technology optimization for machine learning
  - Demonstration

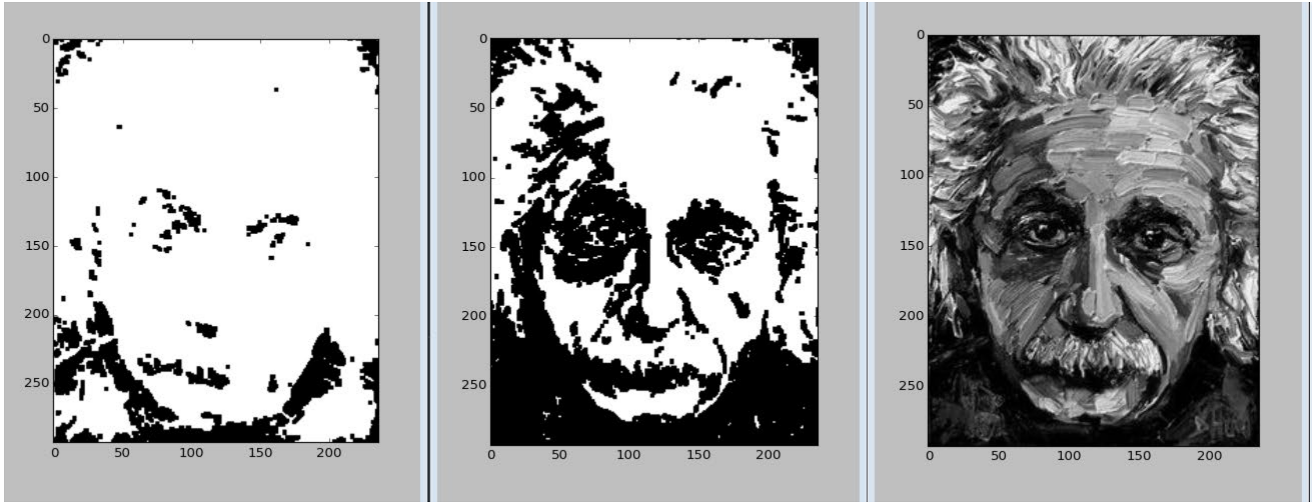
Data structuring, Access control, Federated model

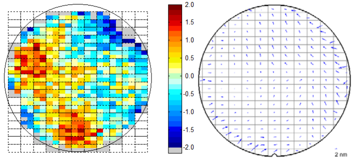


MACHINE LEARNING ON METROLOGY DATA – GUIDANCE

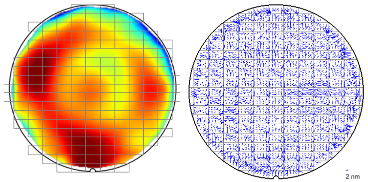


MACHINE LEARNING FOR SMART METROLOGY





Balanced sampling to optimize throughput without compromising on information quality



Can we go further to predict electrical impact ?

(just impact not yield)

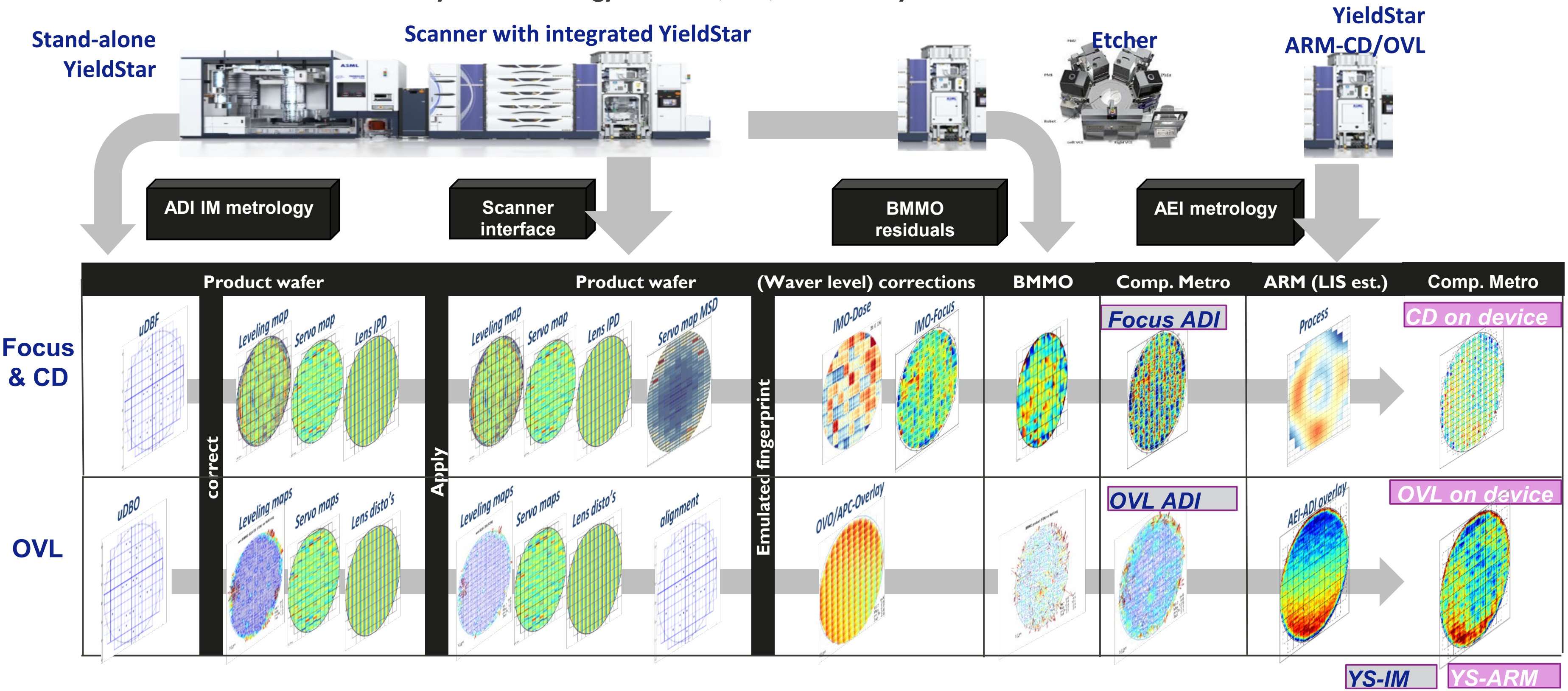
- Measure less but in a smart way so that full wafer behavior can be predicted accurately
- Use ML models to reduce sampling and determine sampling spatial density to get the correct complete picture

imec

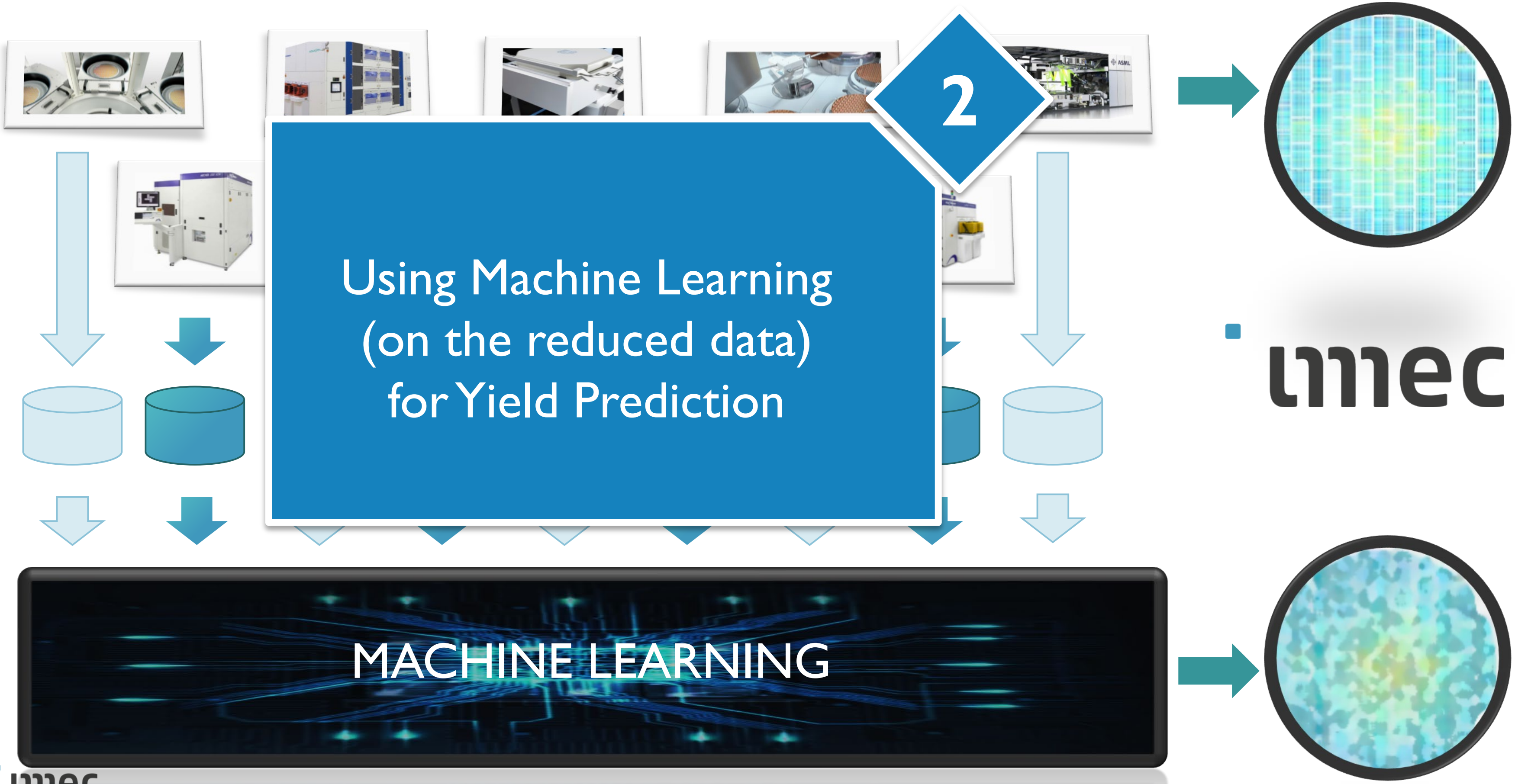
COMPUTATIONAL METROLOGY: HYBRID MAPS CONCEPT

PREDICTIONS FOR FOCUS, OVL & CD FOR EVERY WAFER POINT BASED ON BUDGETS FROM KNOWN CONTRIBUTORS

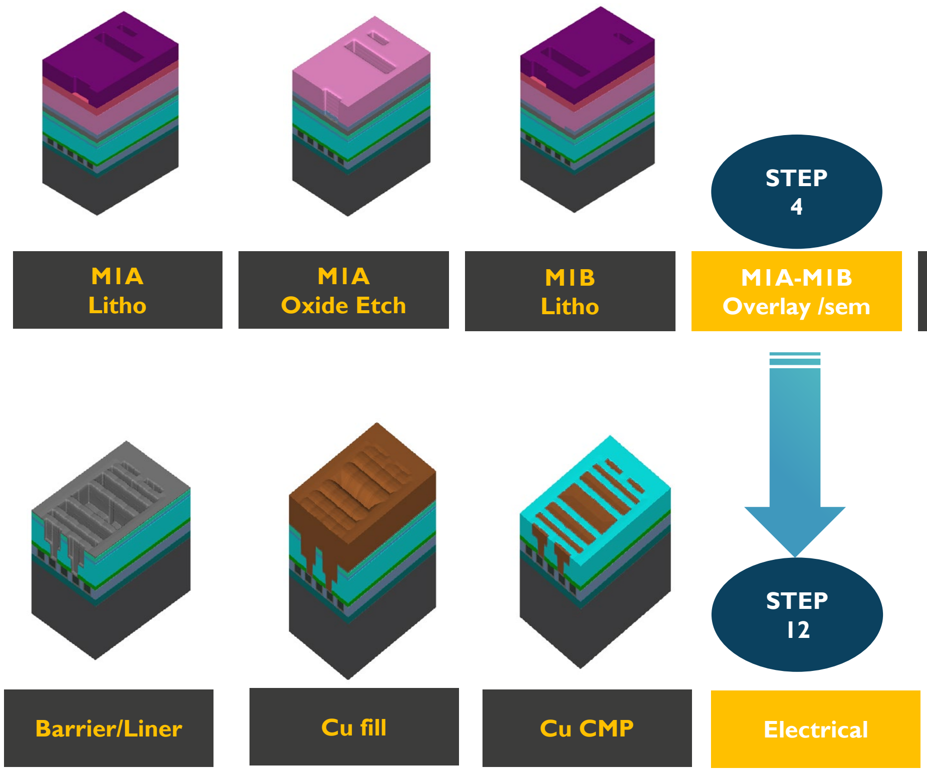
"Efficient hybrid metrology for focus, CD, and overlay" W.T.Tel. SPIE 2017



MACHINE LEARNING ON METROLOGY DATA – PREDICTIVE



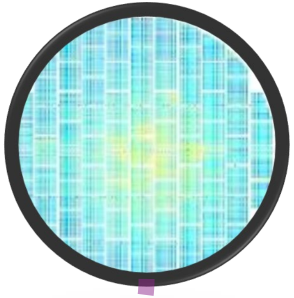
FEASIBILITY STUDY – PROCESS FLOW AND MEASUREMENTS



Data collected in steps 4/8/12 are used for the machine learning exercise

Goal: Early prediction at step 4 the Electrical performance at step 12

FEASIBILITY STUDY

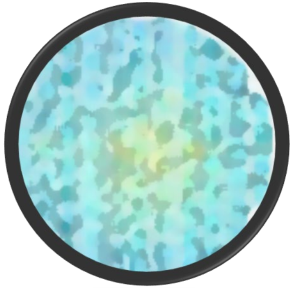


Data

- 4 Wafers
- Metrology Overlay and CD Data from step 4, 8, 11 and 15
- Electrical Measurements

Method

- Use 3 Wafers to train ML model
- Predict electrical measurements of the 4th wafer based on overlay data
- Using 5 different machine learning techniques
  Extra-Trees produced the best results

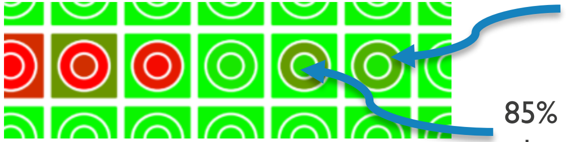


PRELIMINARY RESULTS

- PREDICTIONS ARE ALREADY GOOD

  GIVEN THE LIMITED AMOUNT OF DATA

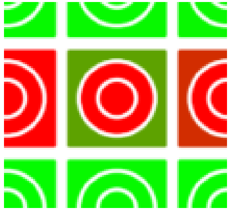
- CAN ALSO GIVE PROBABILITIES



5% sure about the prediction

85% sure about the prediction

- AMELIORATE ELECTRICAL MEASUREMENTS ?

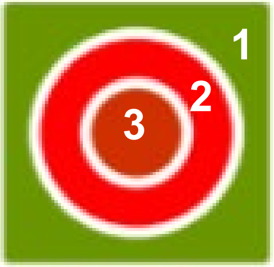


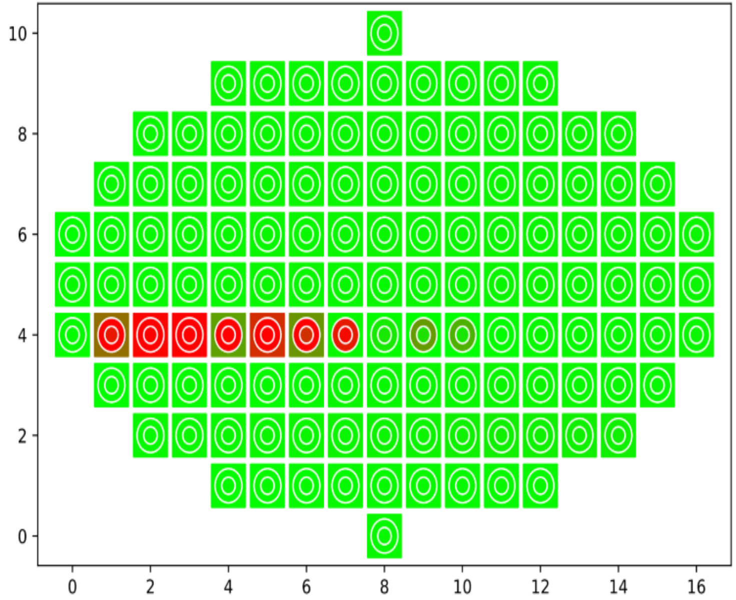
(1) REAL ELECTRICAL MEASUREMENTS

PREDICTED ELECTRICAL MEASUREMENTS

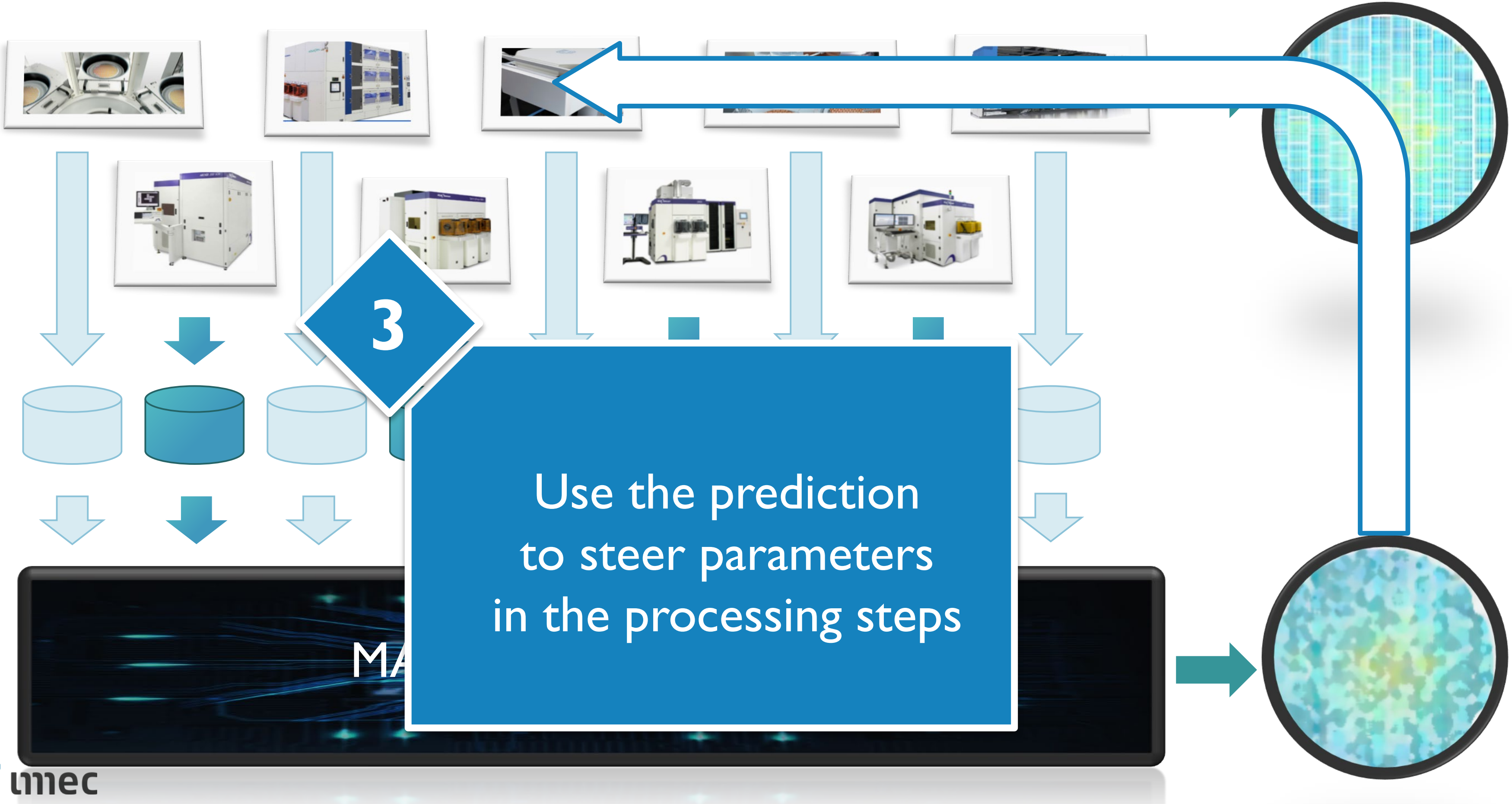
(2) AFTER STEP 4

(3) AFTER STEP 8



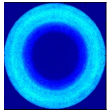


MACHINE LEARNING ON METROLOGY DATA – PROCESS CONTROL

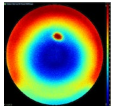


MACHINE LEARNING FOR PROCESS MODELING & PREDICTION

Clean tools

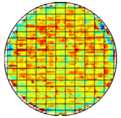


Deposition tools

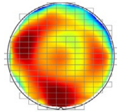


Data repository 1

Lithography tools

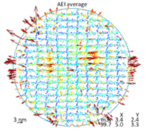


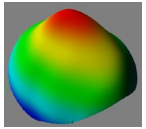
Etch tools



Metrology tools

SEM
Ellipsometry
Scatterometry
Overlay/Focus
XRD/XRR
Mass
Resistivity
Wafer shape

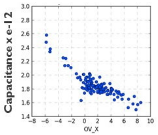


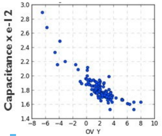


Data repository 2

Electrical Validation

- Resistance
- Capacitance
- I-V characteristics
- Magnetic characterization

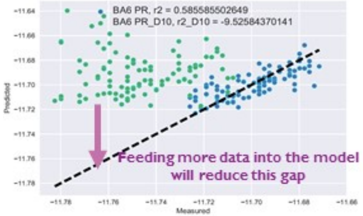




Data repository 3

Prediction

1. What to measure/when to measure
2. Yield Impact



BIG DATA tools For data streamlining

Machine learning on repository data

BIG DATA tools for Data streamlining

Machine learning on repository data

BIG DATA tools for Data streamlining

Machine learning on repository data

1) **Make an appropriate model to link process tool variability with device performance**
2) **Streamlining more data (deposition, lithography, etch, clean) into the model → come up with list of most pertinent parameters**

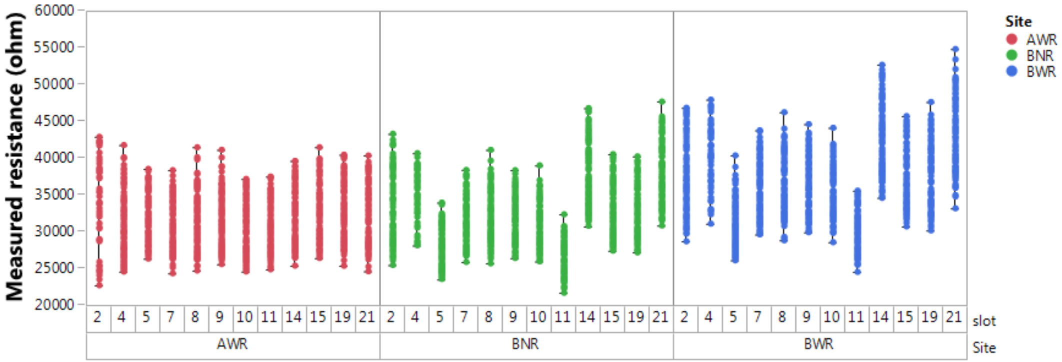
PREDICTING LINE RESISTANCE FROM OCD SPECTRA

OCD MODEL VS MACHINE LEARNING

Learning

Spectra ↓ **Resistance** ↓

Model Setup



Wafers highlighted are used in training set

#	wafer#	DoE
1	2	M1A FEM
2	4	M1B FEM
3	5	Etch v1
4	7	POR
5	8	POR
6	9	POG OVL
7	10	POR
8	11	Etch v1
9	14	Etch v2
10	15	POR
11	19	POR
12	21	Etch v2

Prediction

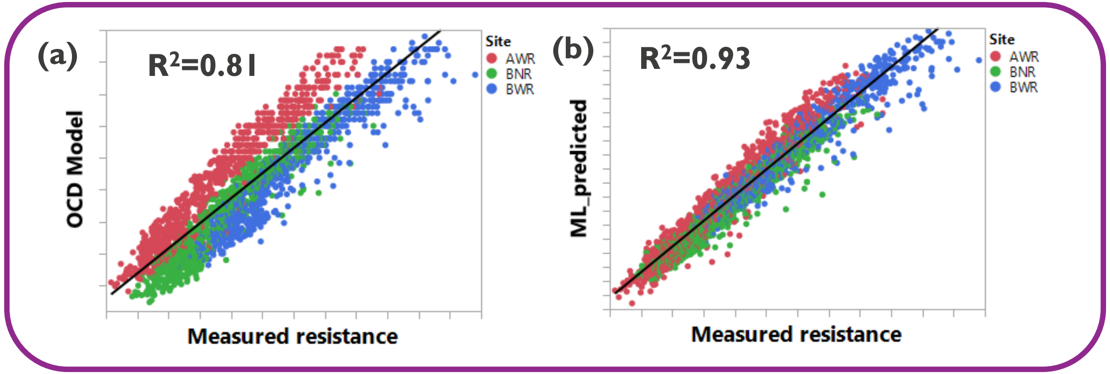
Spectra

↓

Model

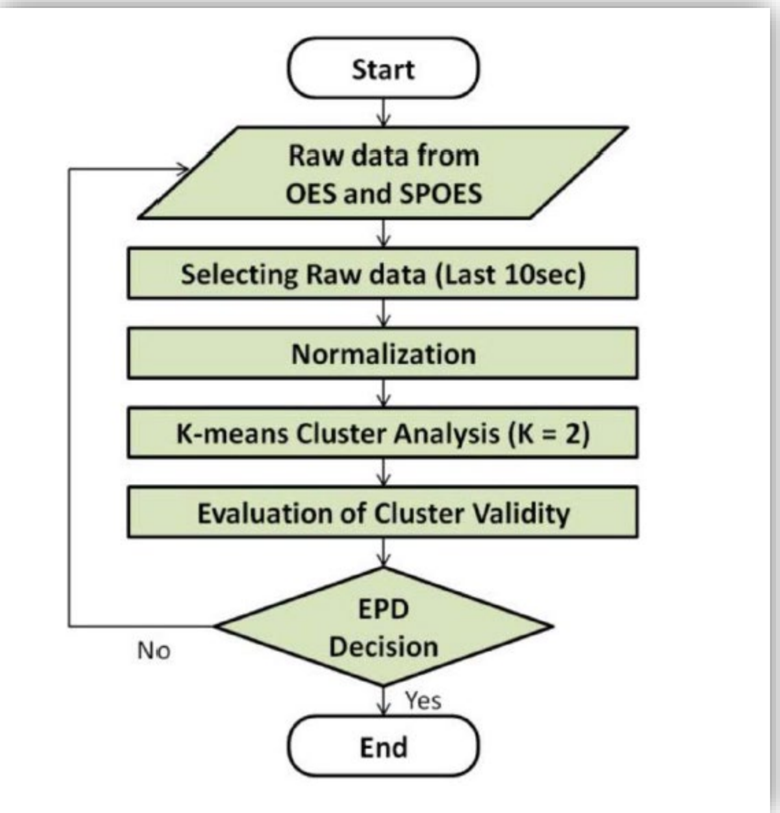
↓

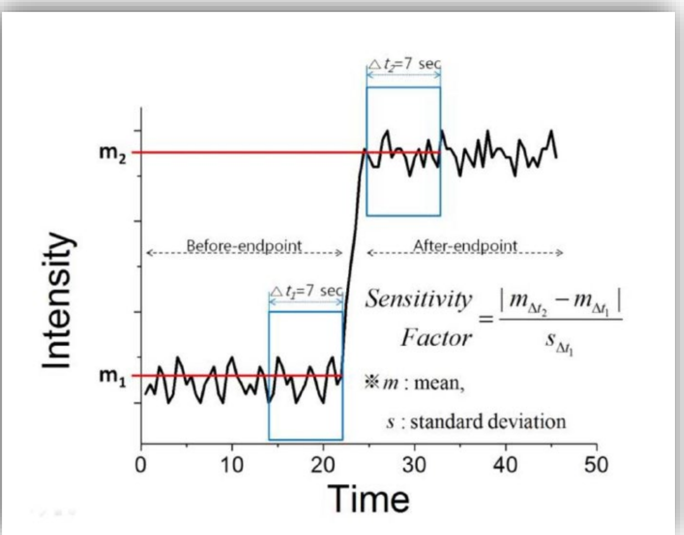
Predicted Resistance



- Machine learning +OCD spectra improves the correlation between measured and predicted line resistance.
- The differentiation between targets reduces. All data on the same linear fit.

MACHINE LEARNING FOR ETCH END POINT DETECTION

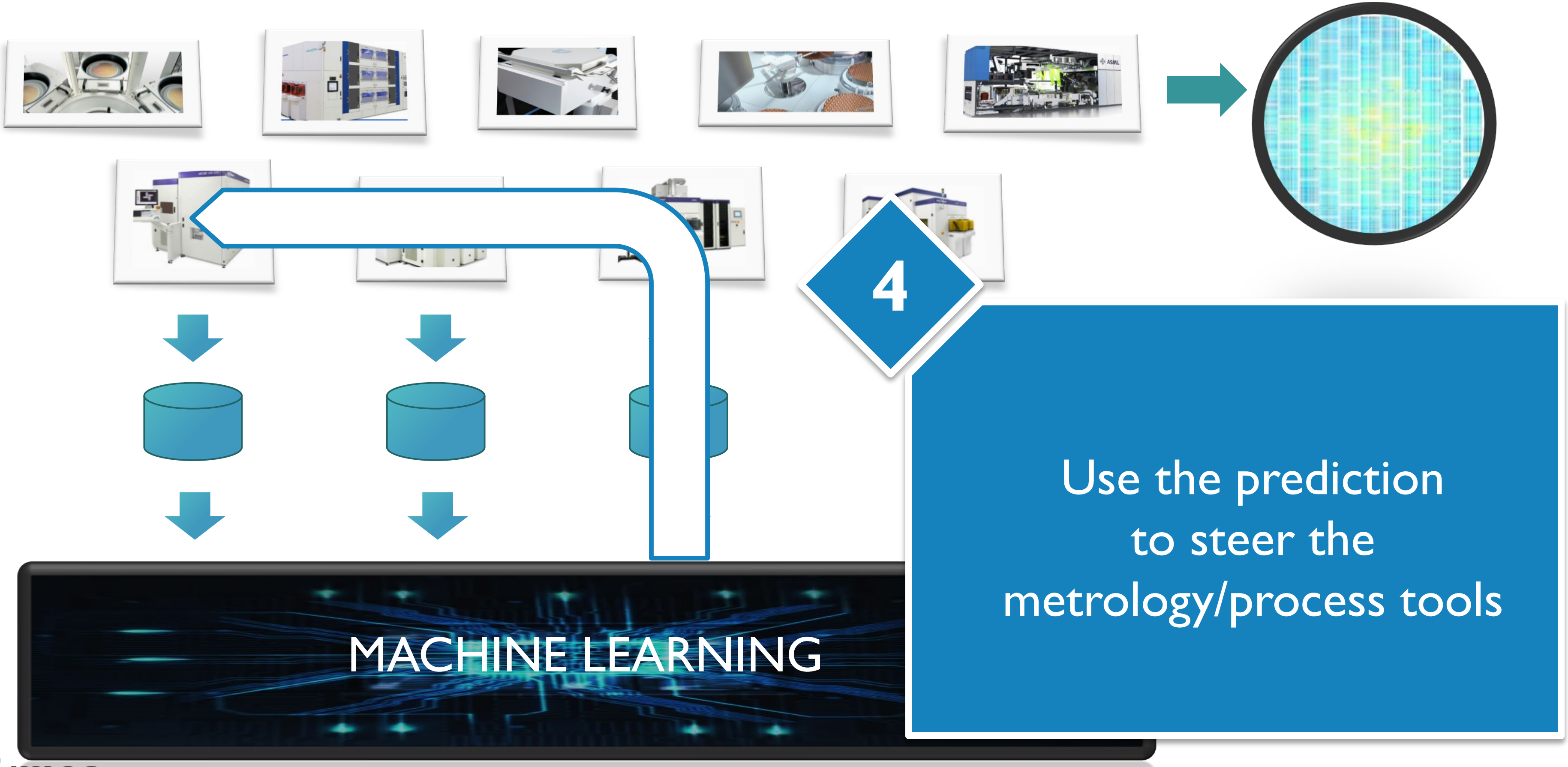




Goals:

1) **Improvement of the end point detection of etch tools**
2) **Check the impact on electrical properties with better EPD**
3) **Show improvement in the whole process flow**

MACHINE LEARNING ON METROLOGY DATA – TOOL MAINTENANCE



MACHINE LEARNING TO DETECT HW FAULT

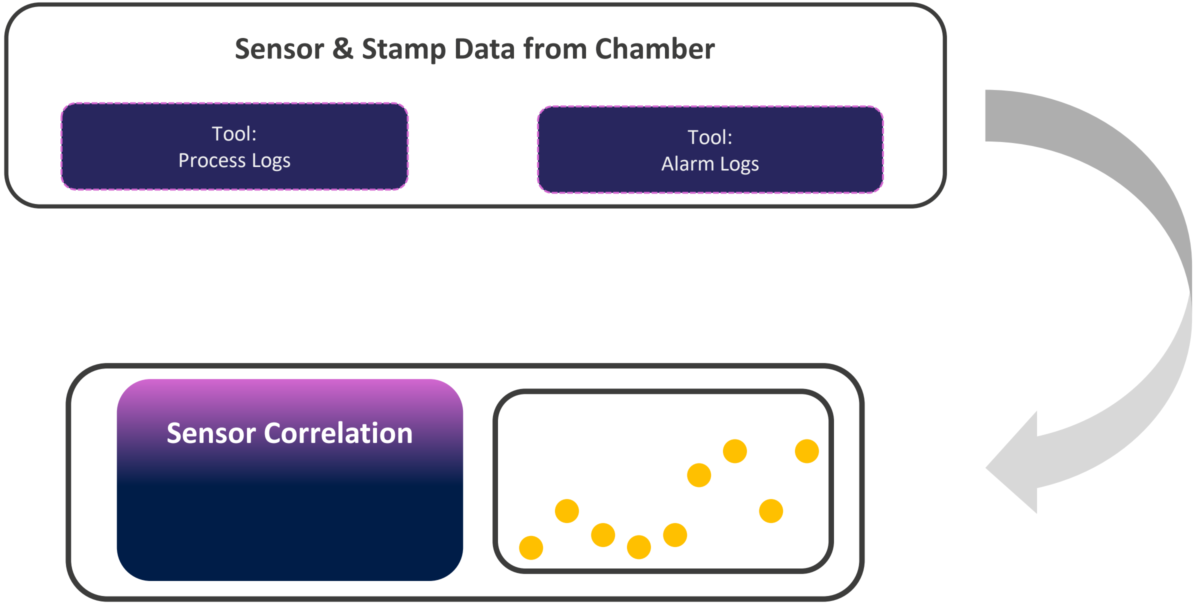
UNBIASED DATA COLLECTION (RAW) FROM THE TOOL

Problem Description:

Part has a lifetime before chamber experiences severe problem

Nominal lifetime is expected to be higher

Product mix and applications being etched can have an influence on the lifetime.



Determine correlation

What are the parameters that have an influence on the sensor data?

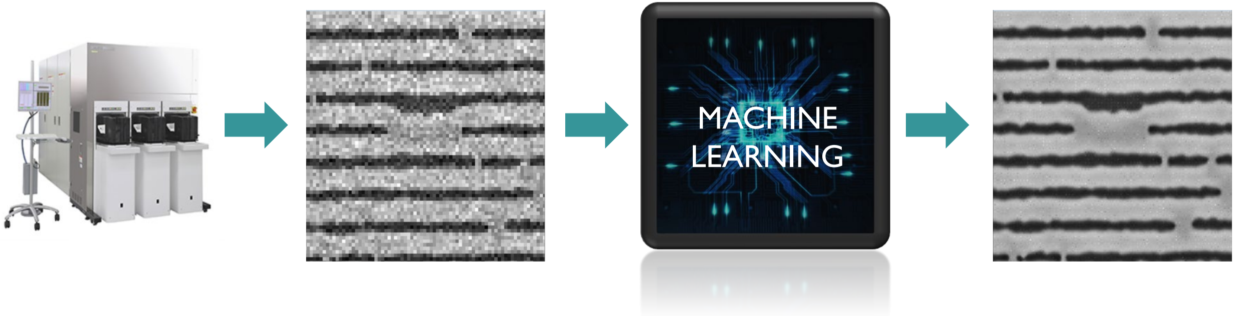
Correlation to:
- **Etch parameters**
- **Etch recipe and lot type**
- **chamber conditions**

MACHINE LEARNING ON IMAGES

ENHANCE METROLOGY CAPABILITIES

5

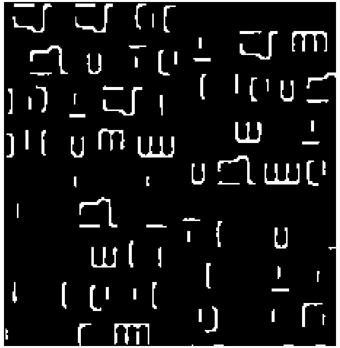
Image enhancement

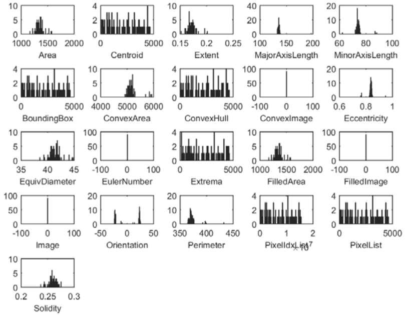


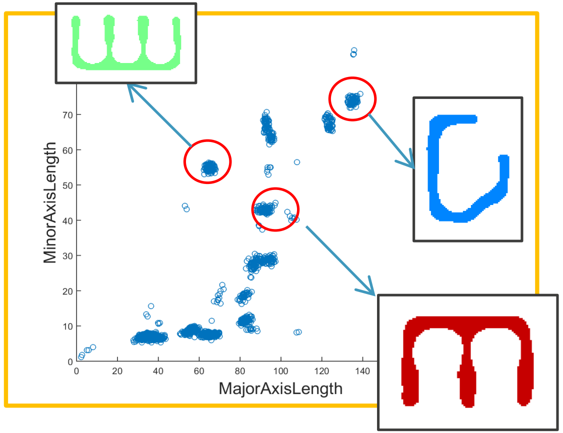
- Machine learning based classification algorithms on Review SEM image
  - Better use of Review SEM images
  - better guide LMC
- Demonstrated capability of DeepNN for SEM images processing
  - Strong correlation of CD from inferred images and CD of original images
  - Defect structure is preserved in the generated image
  - Methodology enables ~16x faster CD-SEM image acquisition for further defect inspection
  - Weak correlation for LWR as high frequency details are not preserved
- Machine learning SEM image denoiser
  - Enable increase of signal to noise ratio in generated images

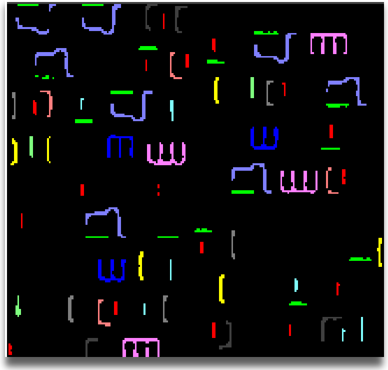
MACHINE LEARNING FOR PATTERN CLASSIFICATION ON SEM IMAGES

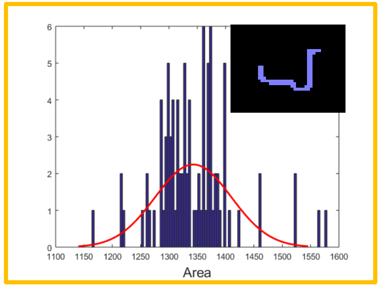
Data consolidation from SEM → **Feature parameter extraction** → **Machine learning algorithm to distinguish features** → **Prediction of shape class/label**











Main objectives:-

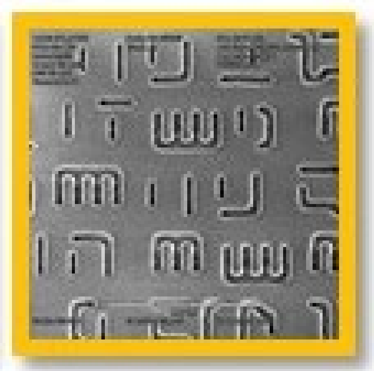
1. **Review-SEM images remain under-utilized – only used for defect verification but not for metrology. Analyze review-SEM images with machine learning approaches to gather much more efficiently process and tool variations and stochastics effects.**
2. **Come up with machine learning based classification algorithms to better guide LMC**

DEEP LEARNING METHODS APPLIED FOR SUPER-RESOLUTION

Goal : Improve resolution for metrology/ inspection while gaining throughput

Optical images/patches

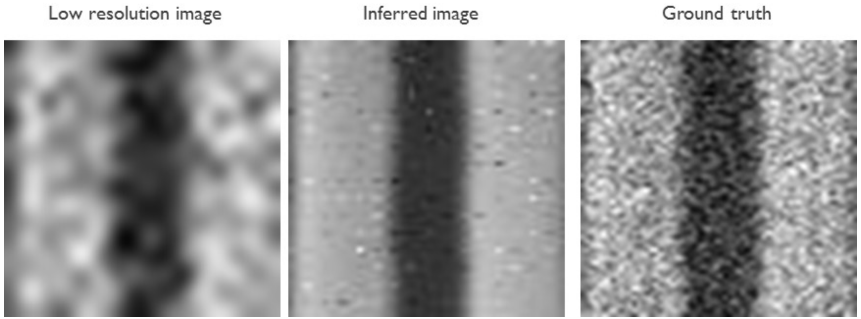
Supernova 2, post M1A
(optical patch)



Supernova 2, post M1A
(E-beam image)

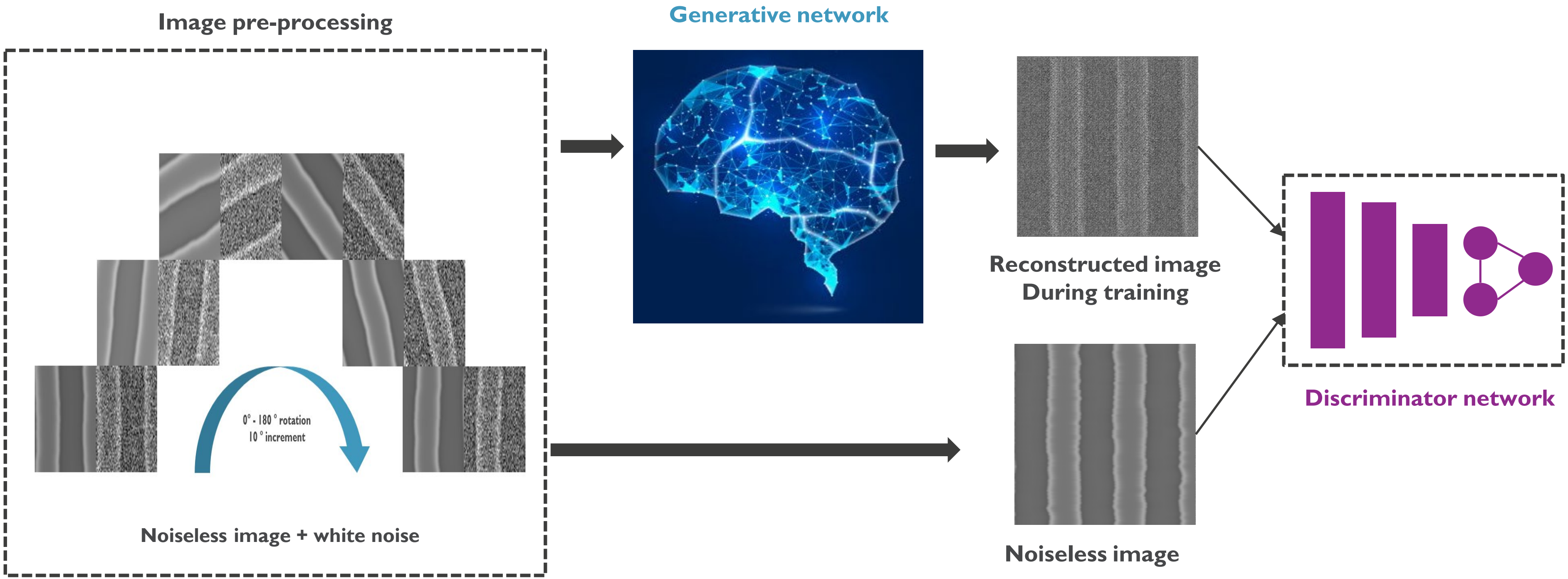
- **Key issue sub N-14 nodes is that SEM review is a must to understand the defect.**
- **Can we get a higher resolution of some optical patches to understand the location of the defect and use it for improving classification**

SEM images



- **Key issue is CD-SEM time/throughput and impact on resist layers when exposed for too long with E-beam**
- **Can we get a higher resolution CD-SEM e-beam image by scanning with bigger pixel size or less number of frames**

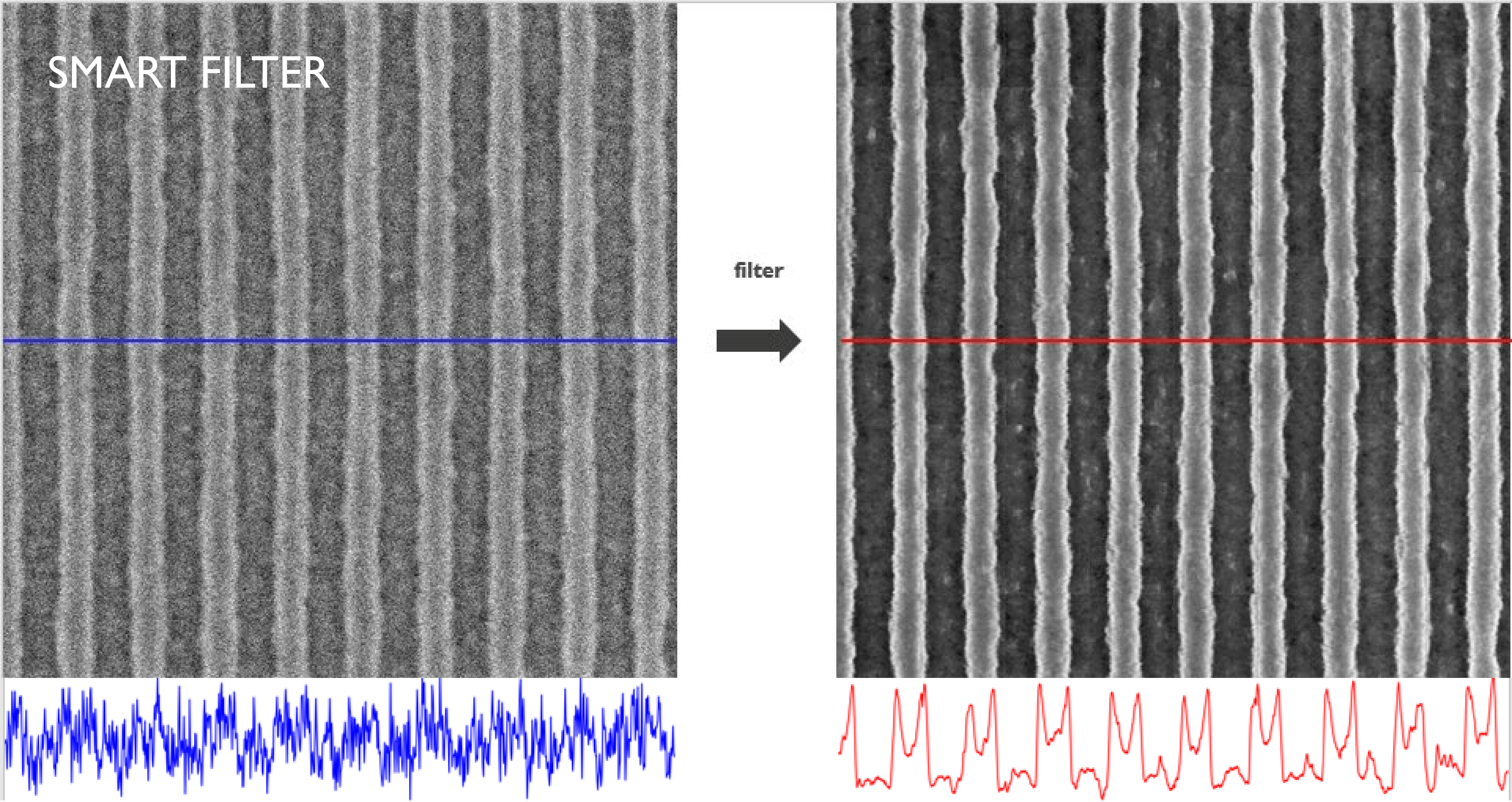
NOISE REDUCTION USING DEEP LEARNING
EMPLOYING GENERATIVE-ADVERSARIAL-NETWORKS



Forward flow of information and network architecture

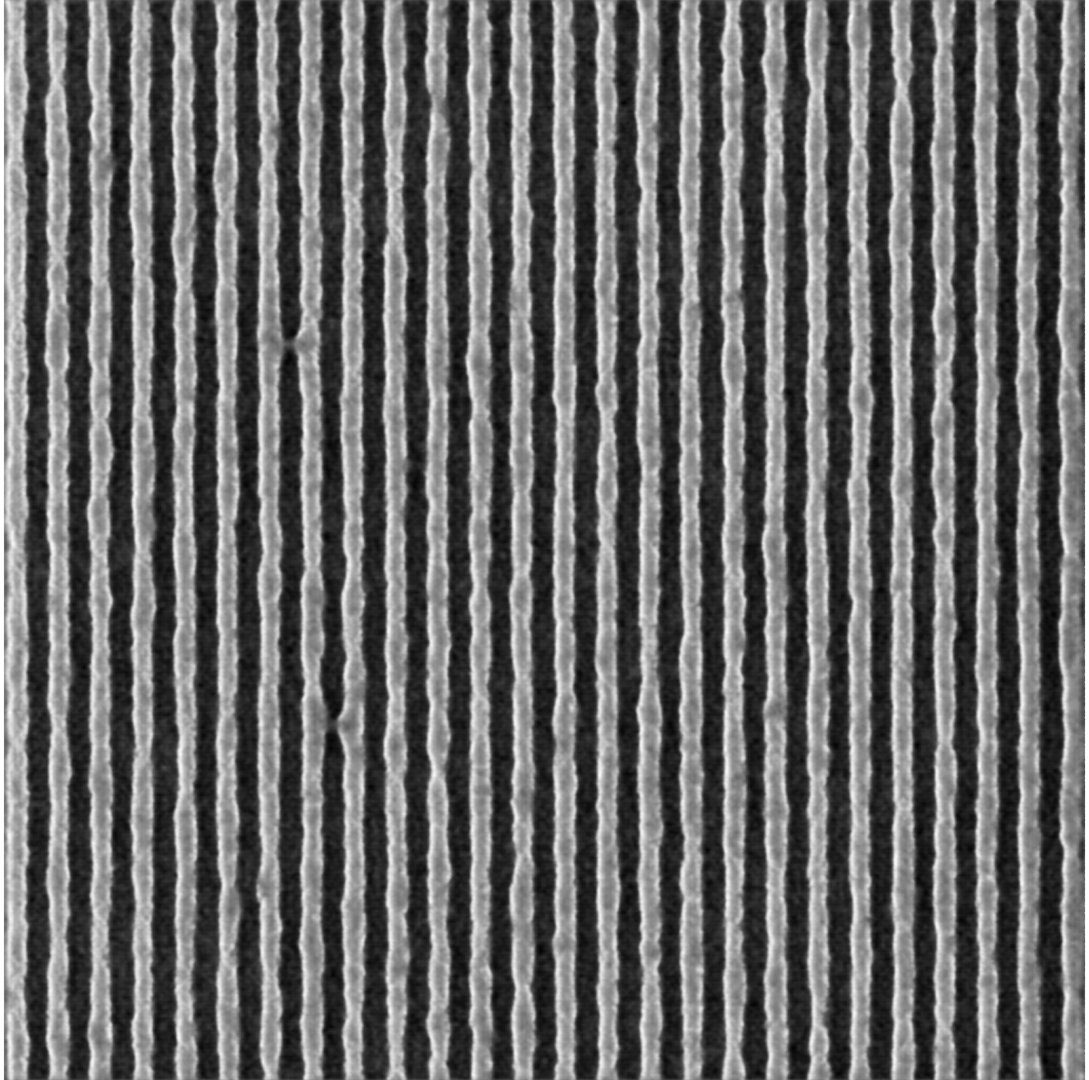
Generation pairs of synthetic and noisy images
~30K images used for training

SMART FILTER



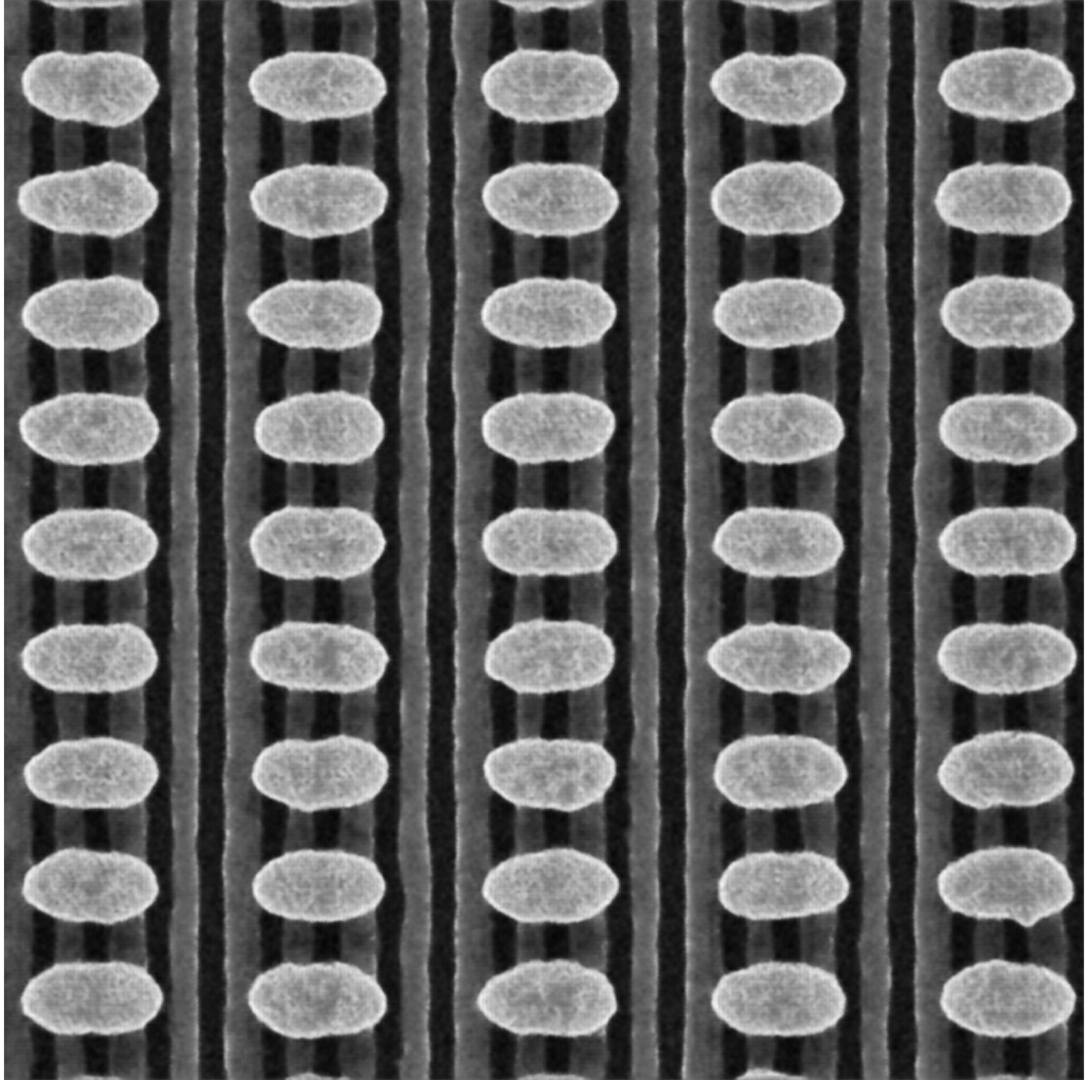
EUV Litho

Defect can be enhanced and facilitate its detection



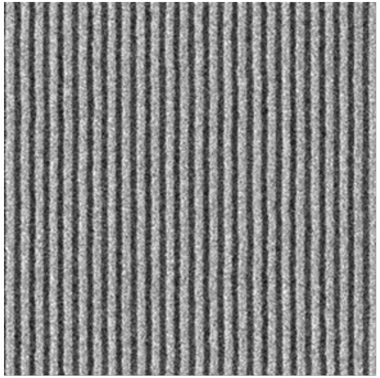
Block on SAQP

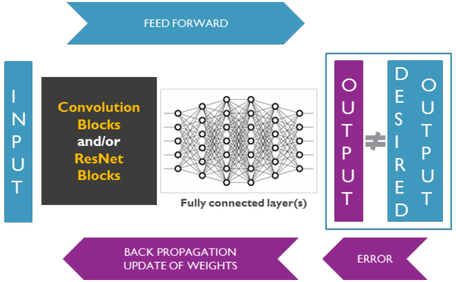
Contrast of lines under blocks has changed



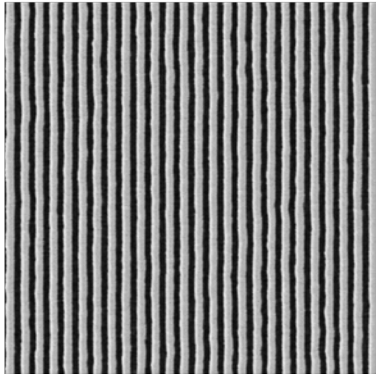
DEEP LEARNING ENABLED IMAGE PROCESSING

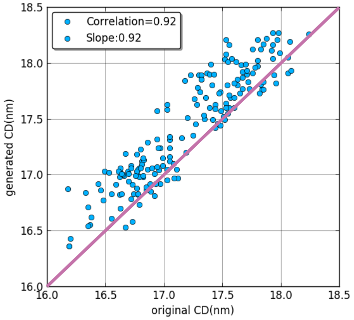
Low resolution input image



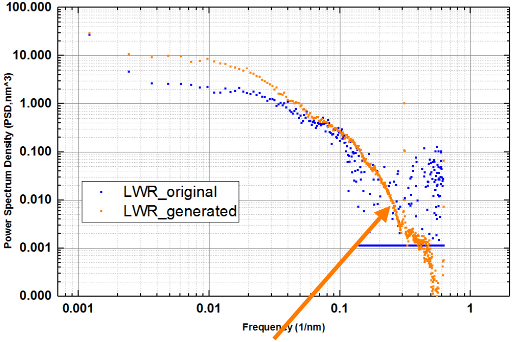


High resolution generated image





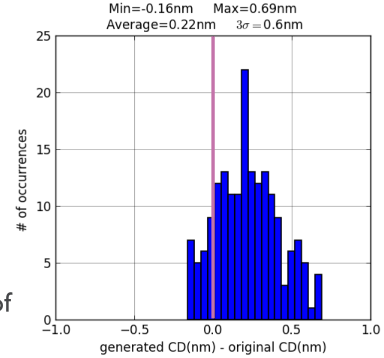
Strong correlation of measured line CD



Breaching the noise plateau

Machine learning assisted metrology:

1. Resolution enhancement of CDSEM images
2. Smart filter - deep learning powered SEM image denoiser. Deep learning enabled increase of signal to noise ratio in generated images
3. Machine learning assisted image fusion for contrast enhancement of SEM images



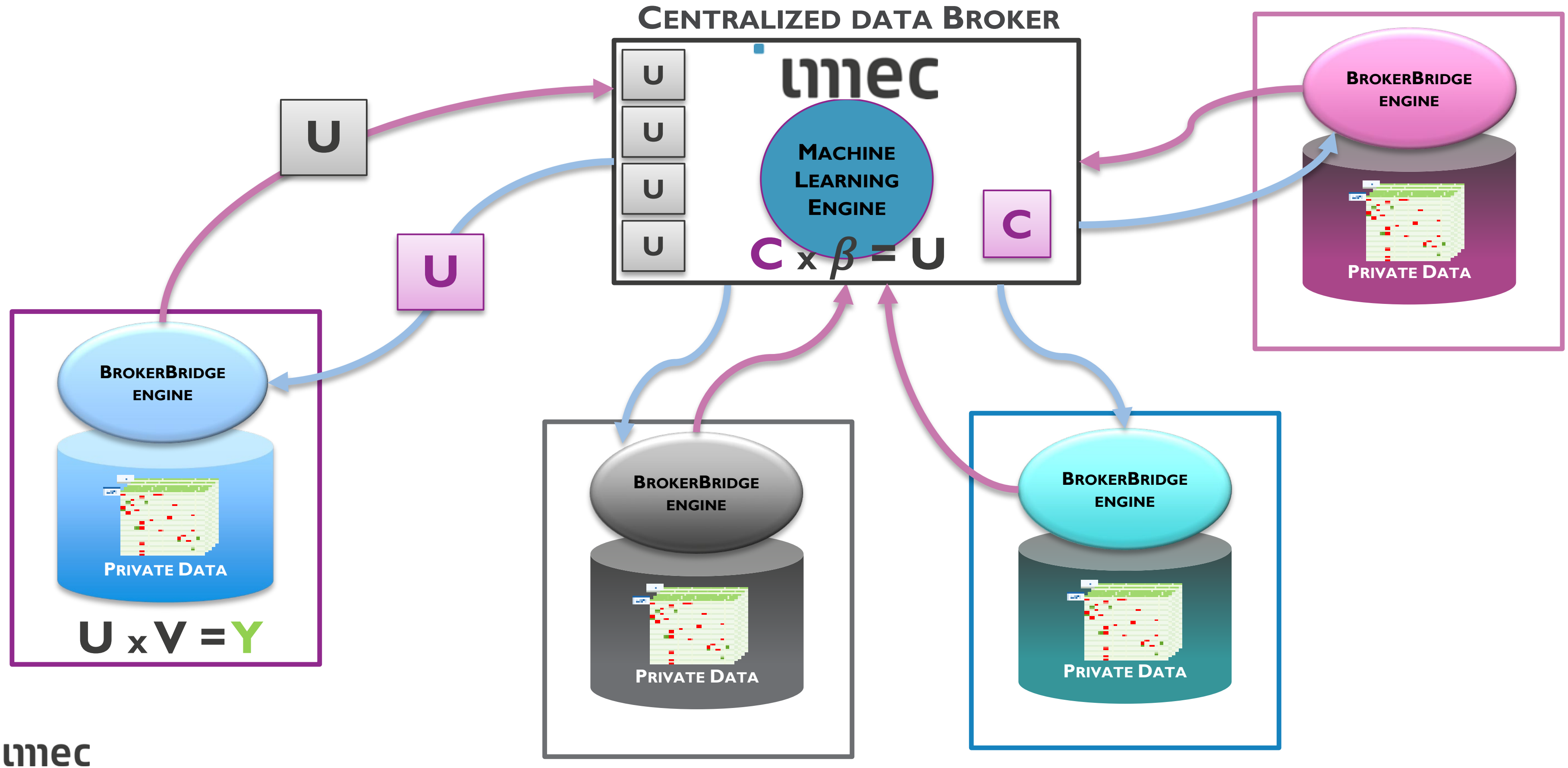
Small residuals <1nm

6 PRIVACY PRESERVING MULTIPARTY MACHINE LEARNING

- In our industry, machine learning activities are investigated in silo
  - Because some of the data contains IP (Supplier or chip makers)
  - Because the algorithm implementation might generate money for the one developing the solution

- But it prevents us to use machine learning to its maximum efficiency
  - Core knowledge of different parties is not sharable (between suppliers or between chip makers and suppliers)
  - If the community could collaborate with their data and their knowledge AND preserving their intellectual properties, machine learning could reach a new level

6 PRIVACY PRESERVING MULTIPARTY



BUT …

HOW TO TEACH THE MACHINE?

- https://www.bbc.com/news/science-environment-47267081

Science & Environment

AAAS: Machine learning 'causing science crisis'

By Pallab Ghosh
Science correspondent, BBC News, Washington

- https://www.techtimes.com/articles/229660/20180608/mit-creates-worlds-first-psychopath-ai-fed-with-gruesome-reddit-content.htm

MIT Creates World's First Psychopath AI, Fed With Gruesome Reddit Content

8 June 2018, 7:48 am EDT By Alexandra Burlacu Tech Times

- Biased learning sets lead to wrong conclusions
- The outcome of machine learning must be verified by engineers to verify the physical meaning of the “intelligent” analysis

CONCLUSION

SO FAR...

- Machine learning algorithm can be useful, it is happening and it is a huge opportunity
- It helps extracting low intensity signals out of noise

- Final results (i.e. electrical, maintenance) can be predicted earlier
- Tool performance can be improved
- Metrology sampling can be optimized
- More information can be extracted from images (increase resolution, reduce noise)

- Privacy Preserving Multiparty Machine learning could be the next step for efficient use of machine learning

- But...
  - The artificial "intelligence" is not there yet
  - A machine can learn only as well as its teacher
  - Artificial "intelligence" does not exclude organic "intelligence". Engineers knowledge needs to be included

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