MADEin4

ECSEL Joint Undertaking

Electronic Components and Systems for European Leadership

imec

1) PRIVACY-PRESERVING AMALGAMATED MACHINE LEARNING (*PAML*) IN THE FAB
2) MACHINE LEARNING WORKFLOW IN THE MADEIN4 PROJECT (FOR PSR TARGETS)

TOM ASHBY 16/11/2021

ASHBY@IMEC.BE

ACKNOWLEDGMENTS

This project has received funding from the Electronic Component Systems for European Leadership Joint Undertaking under grant agreement No 826589. This Joint Undertaking receives support from the European Unions Horizon 2020 research and innovation program and Netherlands, France, Italy, Belgium, Germany, Austria, Hungary and Israel.

DEPARTEMENT
ECONOMIE WETENSCHAP & INNOVATIE

Vlaamse overheid

This research also received funding from the Flemish Government (AI Research Program).

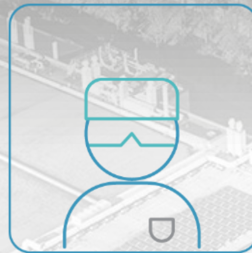
As a **world-leading R&D** hub, we aspire to the impossible and aim for **disruptive innovation**. We maximize societal impact by creating **smart sustainable solutions** that enhance **quality of life**.

At imec, we shape the future.

WORLD-CLASS INFRASTRUCTURE

> 12,000 M² CLEANROOM

CAPACITY



MORE THAN

4,500 SKILLED PEOPLE

FROM OVER 95 NATIONALITIES

A

TRUSTED PARTNER

FOR COMPANIES, STARTUPS & ACADEMIA

OUTLINE

- Privacy-preserving Amalgamated Machine Learning (PAML)
- PAML for virtual metrology
- PAML for anomaly detection
- Pattern Shift Response (PSR)
- PSR modelling and results

cc-by-sa/2.0 - Direction Sign Signpost by D Ivey - geograph.org.uk/p/6515042

WHY PAML?

➔ POOLING DATA IN FABS CAN BE DIFFICULT

- Details of the inner workings of fab machines are ***commercially sensitive***
  - ➔ Equipment suppliers are wary of revealing too much about what happens in their machines
- How fabs use equipment is also ***commercially sensitive***
  - ➔ Fabs don't want anyone, including their equipment vendors, to see how they use their machines
- End result: Information that stays in ***Privacy Siloes***
- Imec's ***Privacy-preserving Amalgamated Machine Learning (PAML)*** can learn from ***privacy-siloed*** data

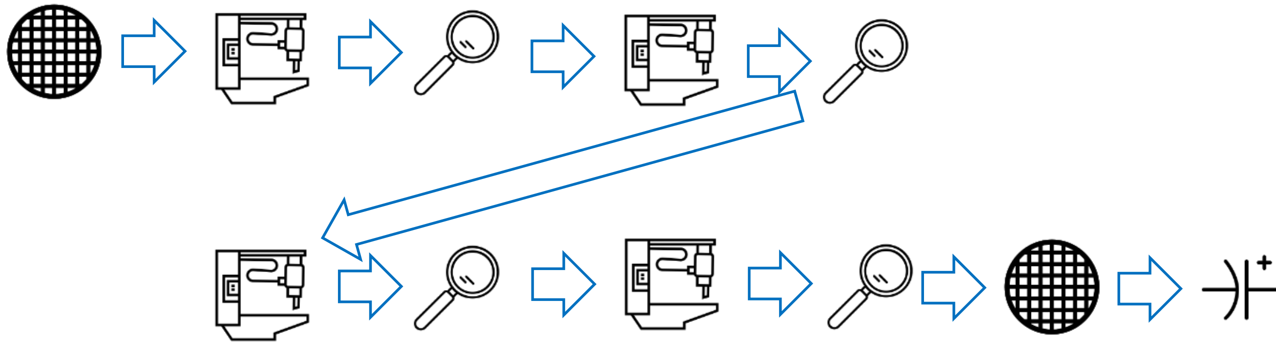
OUTLINE

- Privacy-preserving Amalgamated Machine Learning (PAML)
- PAML for virtual metrology
- PAML for anomaly detection
- Pattern Shift Response (PSR)
- PSR modelling and results

cc-by-sa/2.0 - Direction Sign Signpost by D Ivey - geograph.org.uk/p/6515042

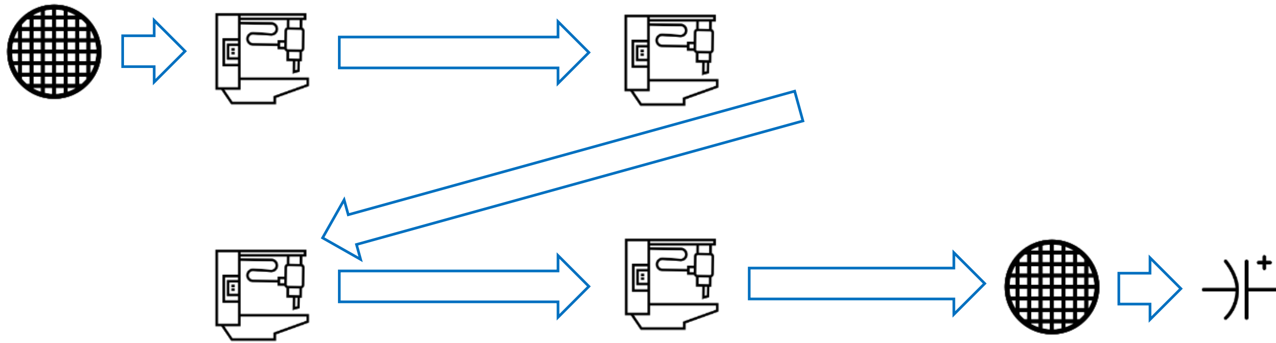
IMEC'S **PAML**

WITH DIRECT METROLOGY



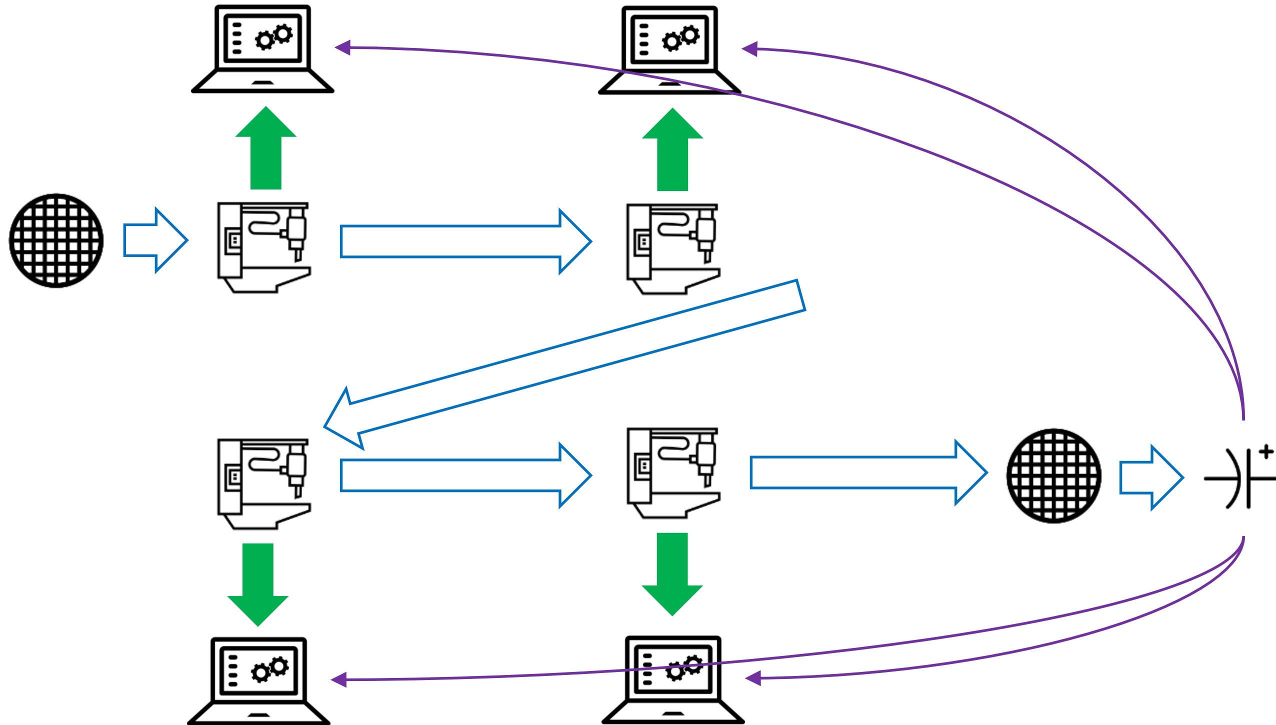
IMEC'S **PAML**

WITH VIRTUAL METROLOGY: ELIMINATE MEASUREMENTS



IMEC'S **PAML**

BUILDING LOCAL PREDICTIVE MODELS

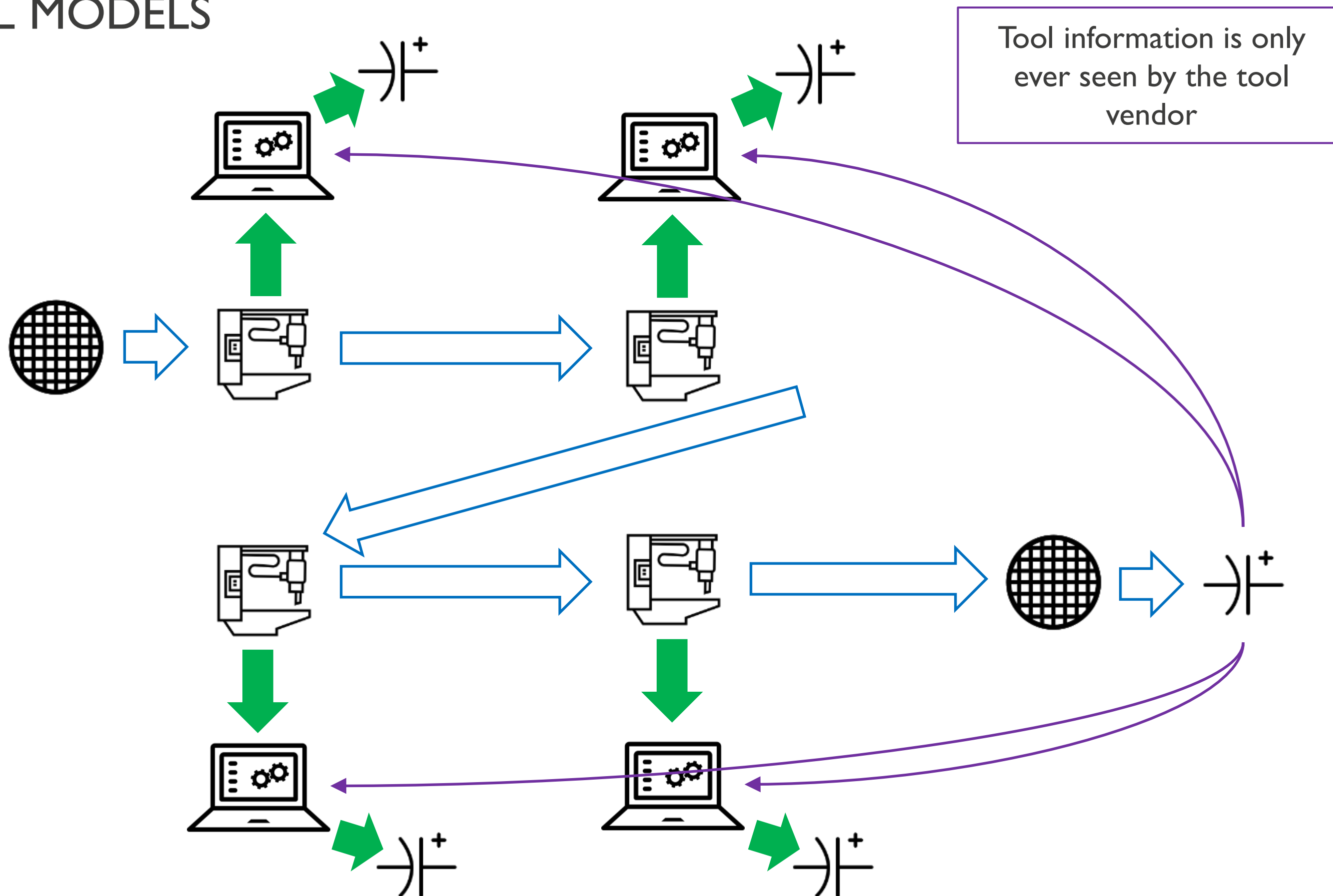


public

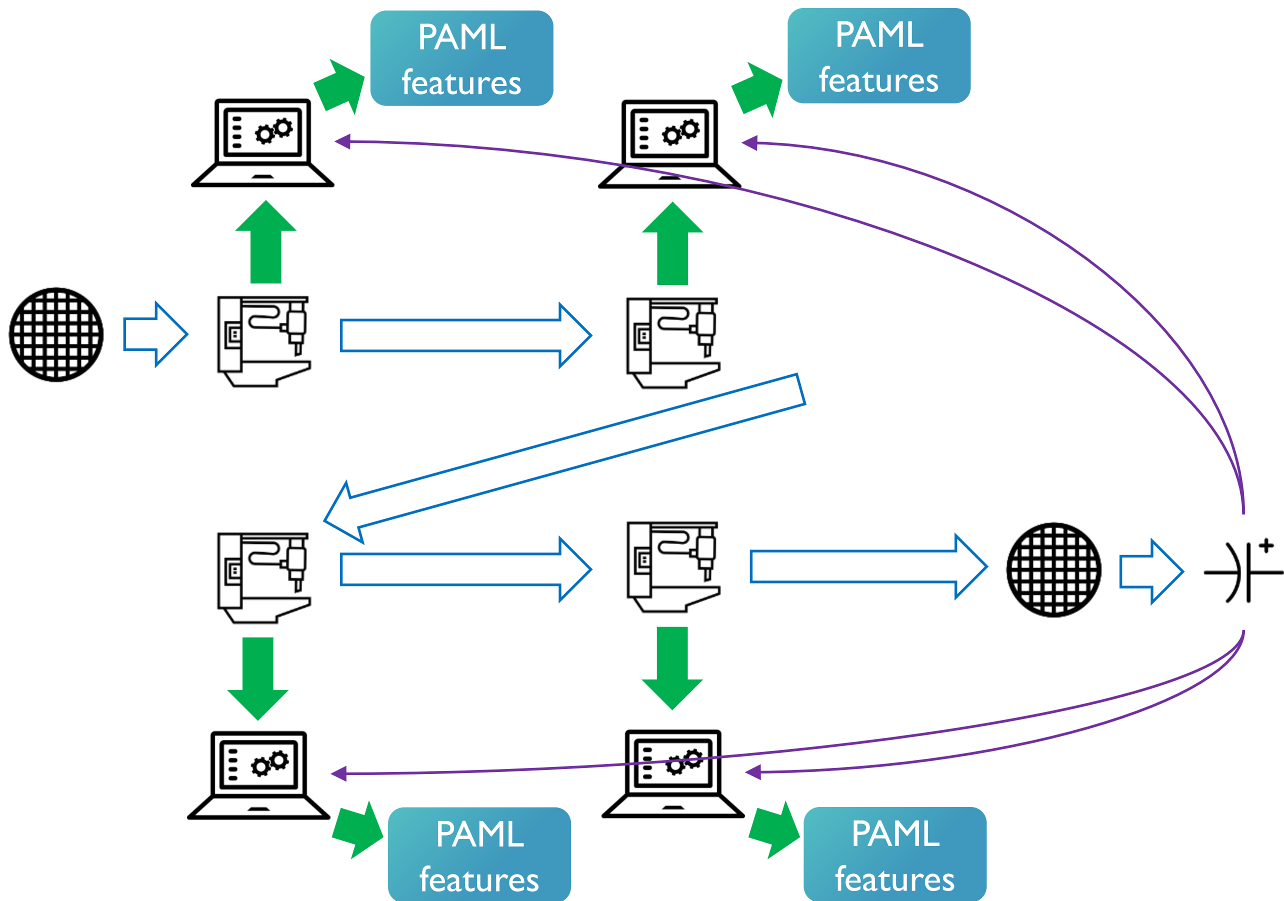
IMEC'S **PAML**

LOCAL MODELS

Tool information is only ever seen by the tool vendor



IMEC'S **PAML** CAN LEARN FROM PRIVACY-SILOED DATA



IMEC'S **PAML** CAN LEARN FROM PRIVACY-SILOED DATA

Tool information is safely shared with the fab

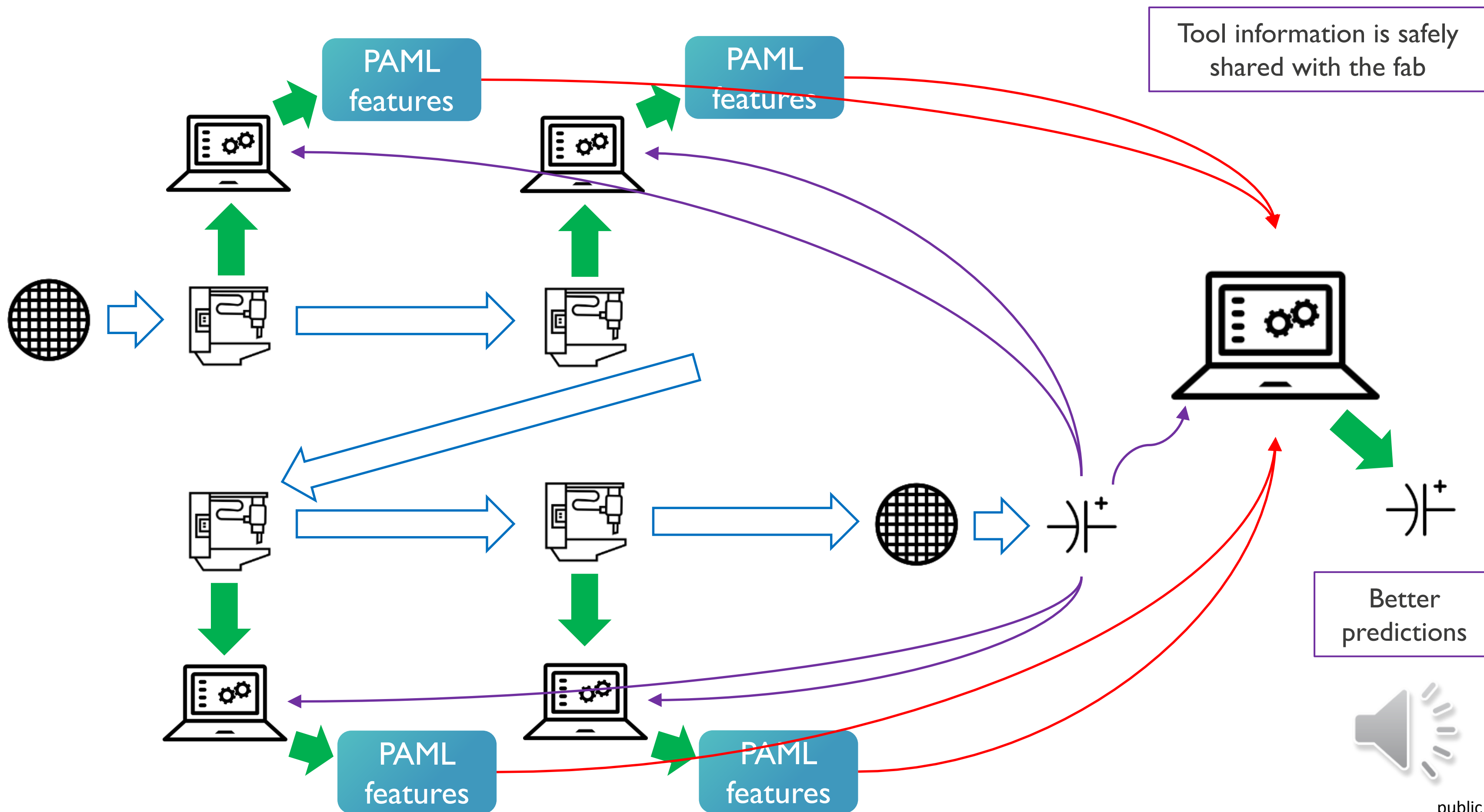
PAML features

PAML features

PAML features

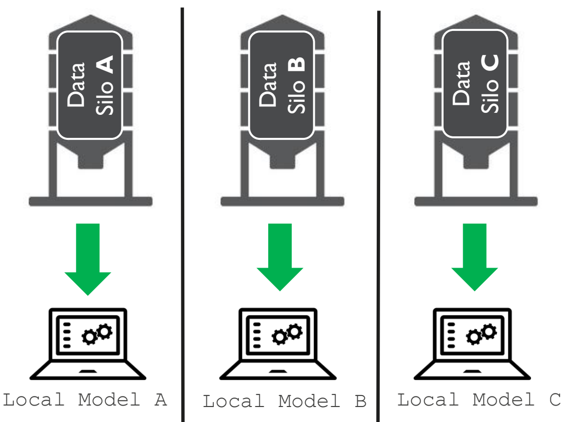
PAML features

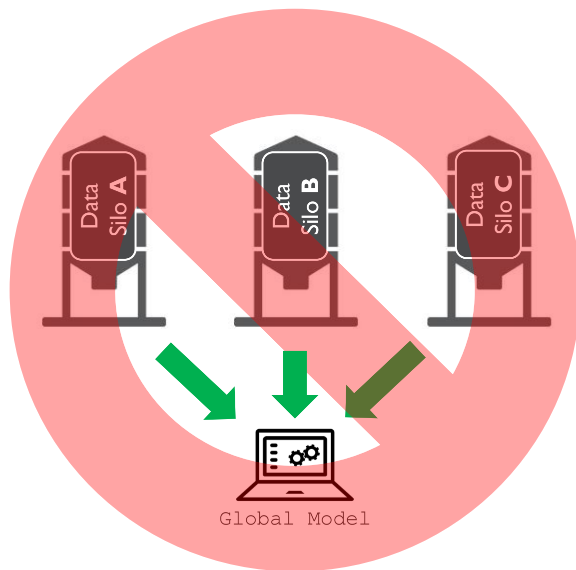
IMEC'S **PAML** CAN LEARN FROM PRIVACY-SILOED DATA

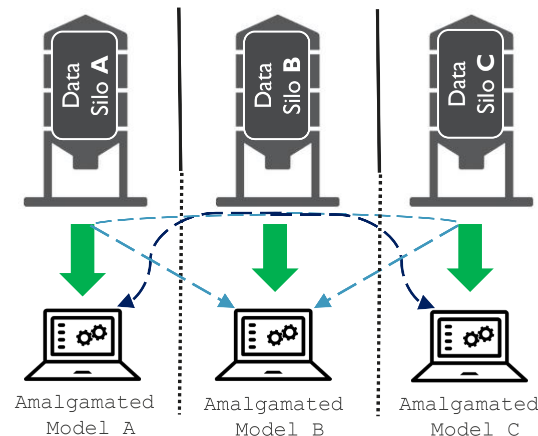


PAML

imec







Local Models

- Respects privacy silos
- Loses performance

Single Global Model

- Best performance
- Breaks privacy constraints ➔ *not possible*

Privacy-Preserving Amalgamated Models (PAML)

- Respects privacy silos
- Performance close to Global Model

OUTLINE

- Privacy-preserving Amalgamated Machine Learning (PAML)
- PAML for virtual metrology
- PAML for anomaly detection
- Pattern Shift Response (PSR)
- PSR modelling and results

TOOL ANOMALIES

AND PREDICTIVE MAINTENANCE ETC.

Anomaly A

Fab A

Fab B

Fab C

Anomaly C

Vendor

- Two different, new operational anomalies in tool
  - Anomaly A in Fab A and Anomaly C in Fab C
- Fabs A and B don't know about anomaly C
- Fabs B and C don't know about anomaly A
- The tool vendor gets some reports of what is going wrong, but doesn't know what is triggering it

IMEC'S **PAML**

LOCAL MODELS

Tool operation is only ever seen by the tool vendor

Anomaly A

Fab A

Fab B

Fab C

Anomaly C

A

C

Vendor

- Fabs can only predict what they've already seen
- Tool vendor still in the dark

IMEC'S **PAML**

BENEFIT FOR FABS AND VENDOR

Anomaly A

Fab A

Fab B

Fab C

Anomaly C

PAML features

PAML features

PAML features

Tool operation is safely shared with the vendor

Vendor

A

C

Better predictions

- Fabs get access to **all anomaly predictions**
- Tool vendor can cross-check for possible underlying causes triggering multiple anomalies

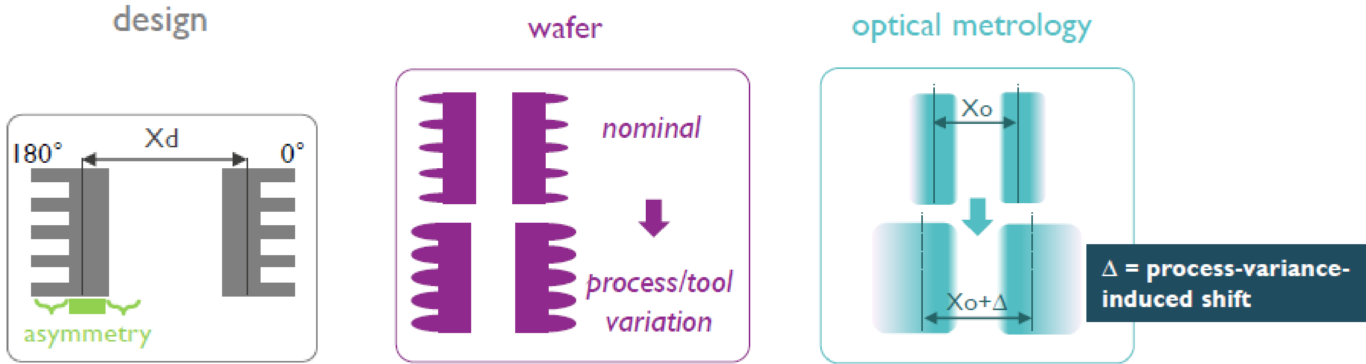
OUTLINE

- Privacy-preserving Amalgamated Machine Learning (PAML)
- PAML for virtual metrology
- PAML for anomaly detection
- Pattern Shift Response (PSR)
- PSR modelling and results

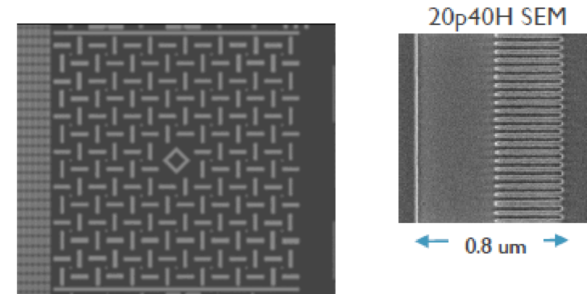
cc-by-sa/2.0 - Direction Sign Signpost by D Ivey - geograph.org.uk/p/6515042

PSR TARGETS

OPTICAL PROXY TARGETS FOR FAST, EXHAUSTIVE METROLOGY

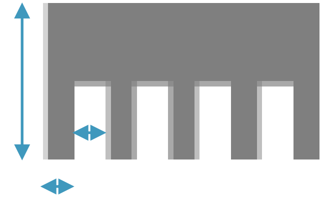


- Patented IMEC technology
  - PSR: ***Pattern Shift Response***
- Advantages
  - Accurate
  - Non-destructive
  - Fast (optical) measurements
  - Small
  - Can be measured at various points during processing

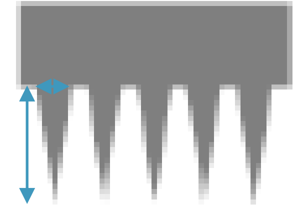


Optical

PSR TARGET DESIGN CHOICES



- Variable parameters of the target include:
  - The family of shapes
    - E.g. comb, triangles, lines… etc etc.
  - Shape parameters
    - Space between teeth
    - Width of teeth
    - Placement of lines
    - … etc. etc.



- What is the best design to monitor a particular aspect of processing?

PSR IN MADEIN4

- IMEC TITAN platform
  - 2 lots processed during the project
- PSR target mix
  - Various PSR target families with various parameters are used
- First metal layer
- Electrical targets
  - Directly measuring predictive ability for a TITAN electrical measurement
    - Resistance of a long meander

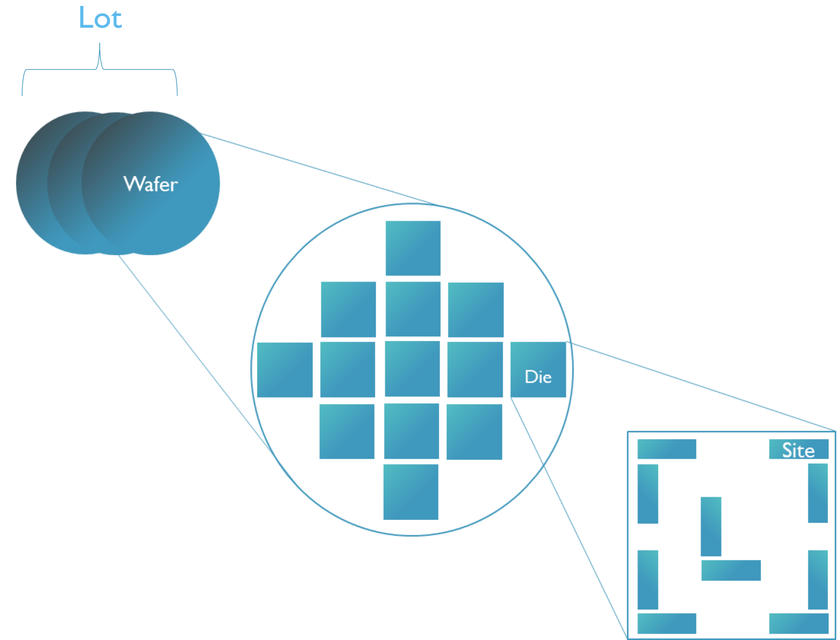
- Work done in the context of the MADEin4 collaboration with ***Mentor***
- ***Thanks to:***
  - Mentor: *Anastasiia Doinychko, Andres Torres*
  - IMEC: *Dorin Cerbu, Kit Ausschnitt, Koen D'Have, Vincent Truffert, Stéphane Lariviere, Anne-Laure Charley*

PSR IN MADEIN4

MODELLING APPROACH

- ML modelling challenges
  1. Hierarchical data
     - Lots, wafers, dies, (target site)
     - Should the hierarchy be represented? How?
  2. Small amounts of data
     - 2 lots
     - 40 wafers
     - ➔ increased risk of overfitting complex models

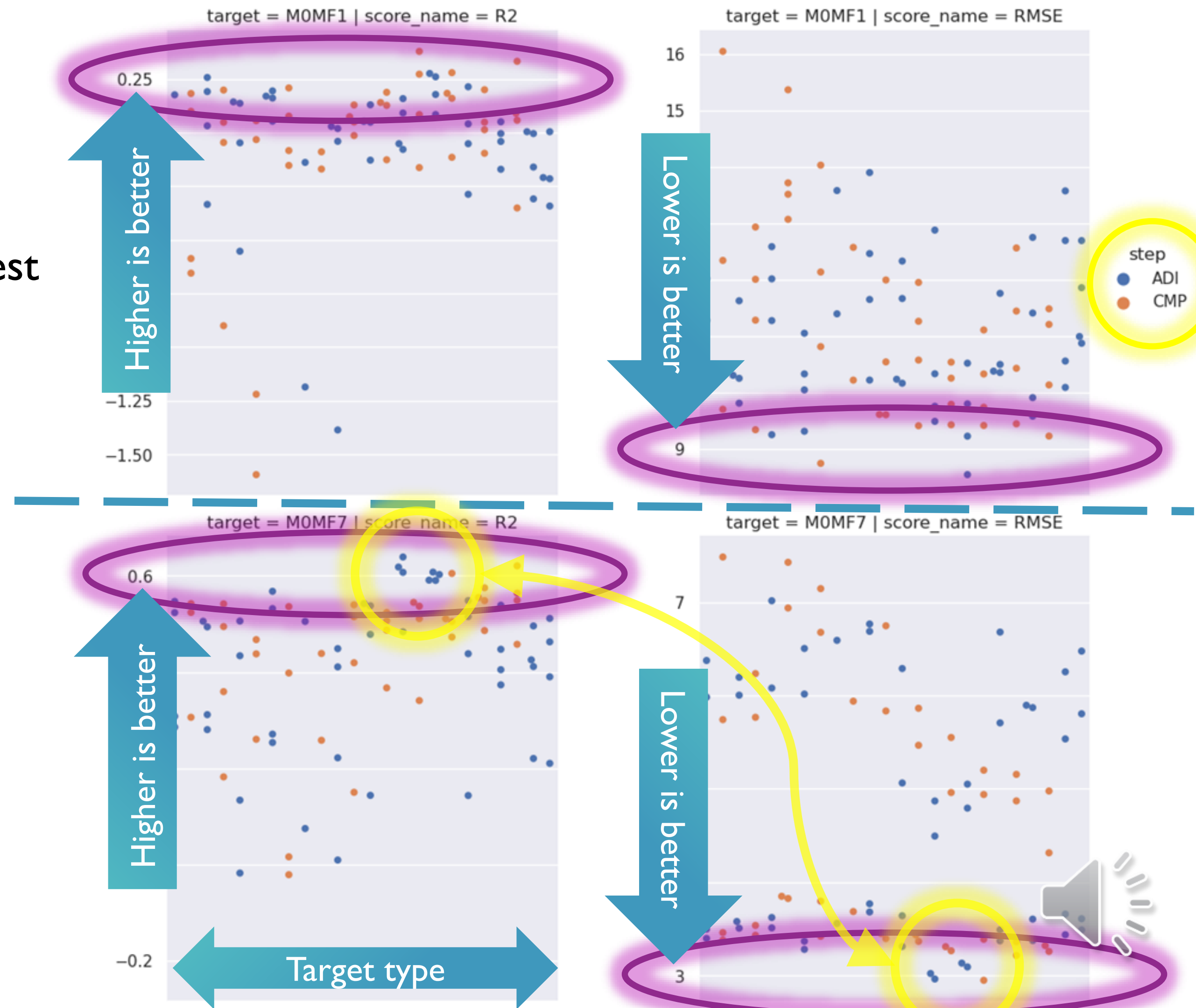
- ML modelling approach
  - Boosted Tree model
  - Die level model
  - Location features
    - Direct representation of die location and wafer
  - Top-level hierarchy (wafer) split



MODELLING RESULTS

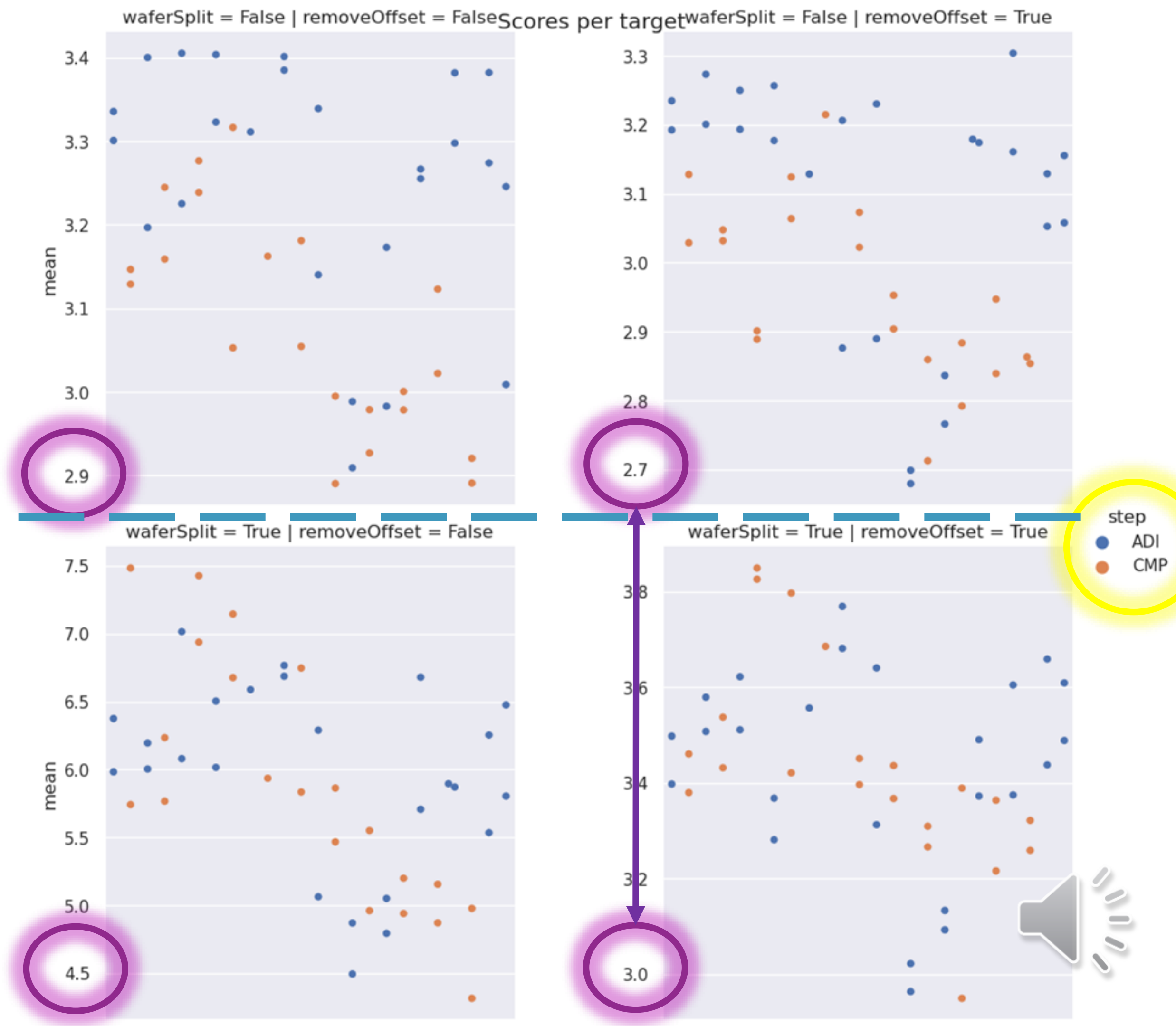
- Comparing best and 2nd best performance
- Split by electrical measurement
  - Above: short meander
  - Below: long meander
- Measurements shown at:
  - Post litho: ADI
  - Post fill & polish: CMP

- *(Metrics: R2 and RMSE)*
  - *R2 and RMSE agree on best*



MODELLING RESULTS

- Zooming in on best electrical measurement
- Compare:
  - Wafer-level split and die-level split
    - Above: die-level
    - Below: wafer-level
  - Mean-centering data per wafer or not
    - **Left**: no centre
    - **Right**: mean centred
  - *(Metric: RMSE)*
- *➔ Wafer split loses some performance*



MODELLING RESULTS

- Zooming in on best optical target
  - Wafer level split
  - (Mean-centred)
- Compare:
  - Predictive accuracy across wafers
  - Each plot is a different wafer when used in the test set
  - (Blue line is best linear fit)

WAFER = 2 | WAFER = 3 | WAFER = 4 | WAFER = 5 | WAFER = 6 | WAFER = 7
WAFER = 8 | WAFER = 9 | WAFER = 10 | WAFER = 11 | WAFER = 12 | WAFER = 13
WAFER = 14 | WAFER = 15 | WAFER = 16 | WAFER = 17 | WAFER = 18 | WAFER = 19

PRED_TARGET

TARGET

MODELLING RESULTS

- Same info as previous plots
- Presented as **residual plots**

➔ Most points fall within +/- 5

  - (roughly 6% error either way)
  - Badly behaved wafers:
    - 2, 3, 5, 6

MODELLING RESULTS

FEATURE IMPORTANCE

- Optical targets are informative
- Position is also important
  - Wafer-level signature
  - Long tail for vertical pos.

- *(Importances shown on wafer-split mean-centred data)*

Feature 39
Radial position
Wafer
Vertical position
Feature 14
Horiz. position
Feature 43
Feature 10
Feature 28
other features

−0.6 −0.4 −0.2 0.0 0.2 0.4 0.6
SHAP value (impact on model output)

High
Feature value
Low

PSR SUMMARY

- PSR targets
  - Are cheap and fast to measure
  - Can be used to predict some electrical measurements
    - (Proof-of-concept)

- MadeIn4 context
  - Feature engineering for PSR targets
    - Evaluation of which targets work the best
    - How to incorporate target features into down-stream models
      - E.g. the cross-virtual metrology of Mentor

OUTLINE

- Privacy-preserving Amalgamated Machine Learning (PAML)
- PAML for virtual metrology
- PAML for anomaly detection
- Pattern Shift Response (PSR)
- PSR modelling and results

imec

embracing a better life

ashby@imec.be