Monotonic Machine Learning (MML) for Lithography Retargeting Layer Generation by Leveraging Contour-Based Metrology

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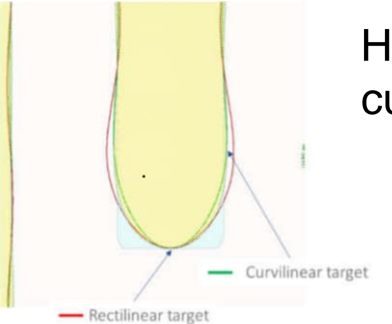
Outline

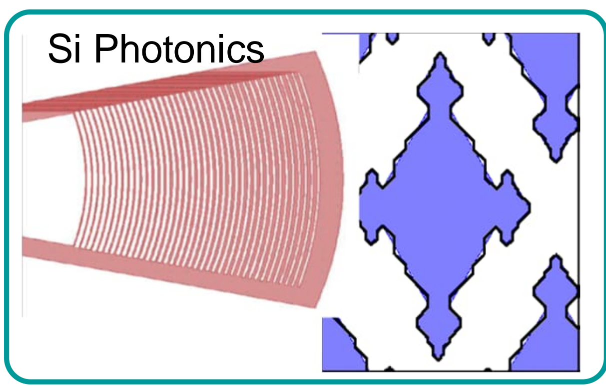
- Introduction
- Problem statements
- Monotonic Machine Learning (MML)
- Dual stage MML guided curvilinear Litho target layer generation
- MML full-chip prediction demo
- Summary

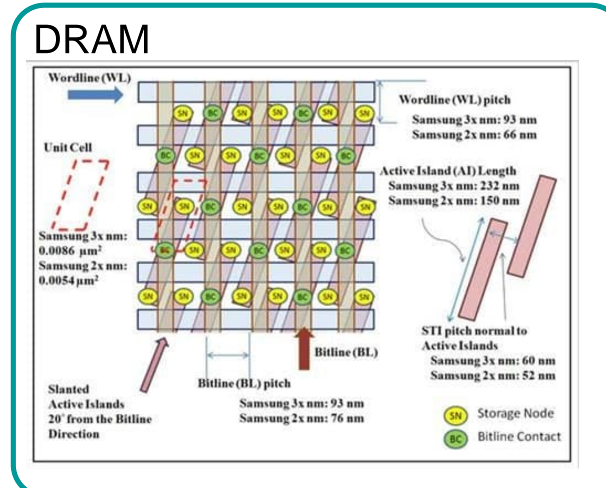
Curvilinear Targeting is Essential for Improved Wafer Accuracy

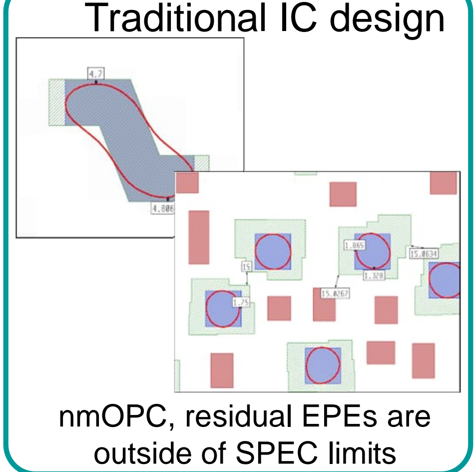
- Curvilinear target is a very useful construct which acknowledges resolution limitations and assists in obtaining most achievably useful wafer results.
  - **Si Photonics designs and AR/VR** include all-angle and curvilinear target shapes that present a challenge for both retargeting and OPC.
  - **Memory designs** can have skew angle targets
  - **Traditional rectilinear IC designs** run into limitations



How to find proper curve target?







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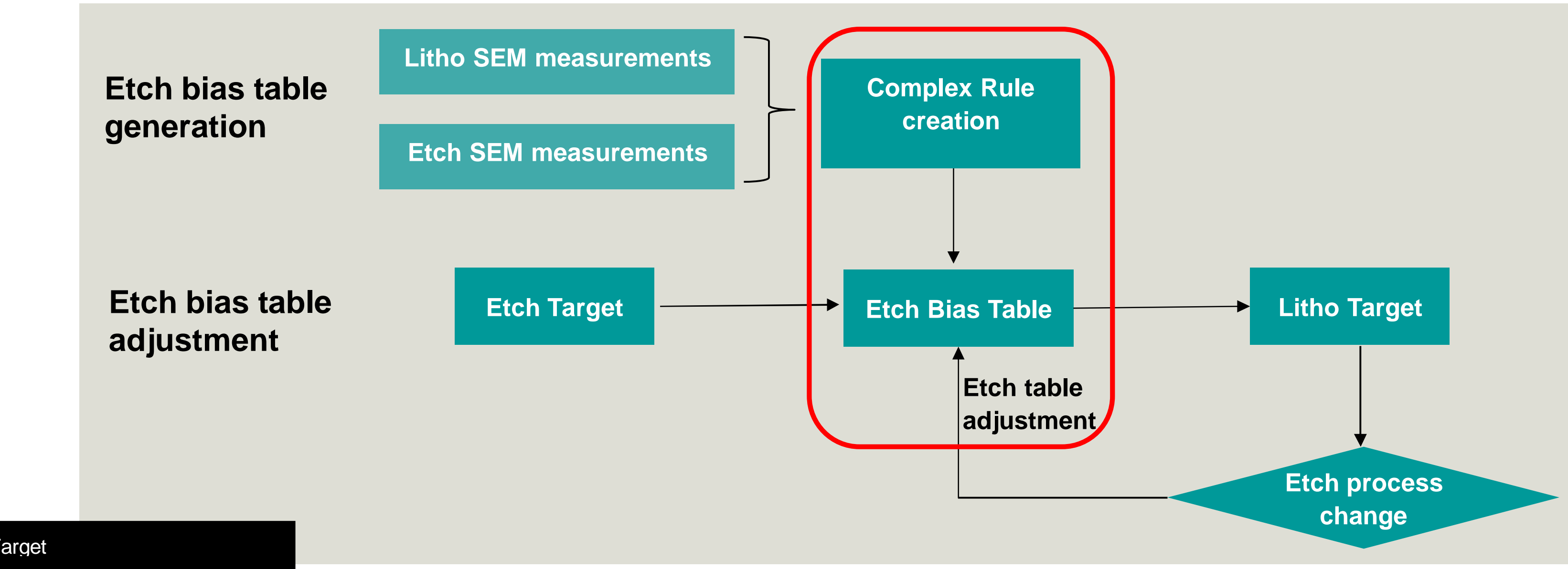
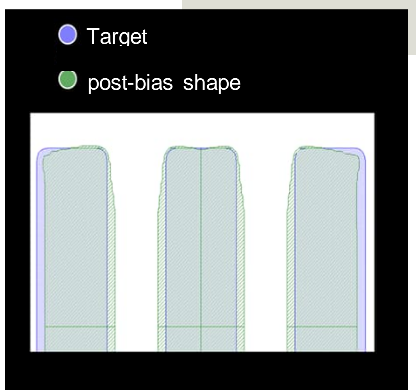
The Gauge Based Retargeting Rule Table Generation



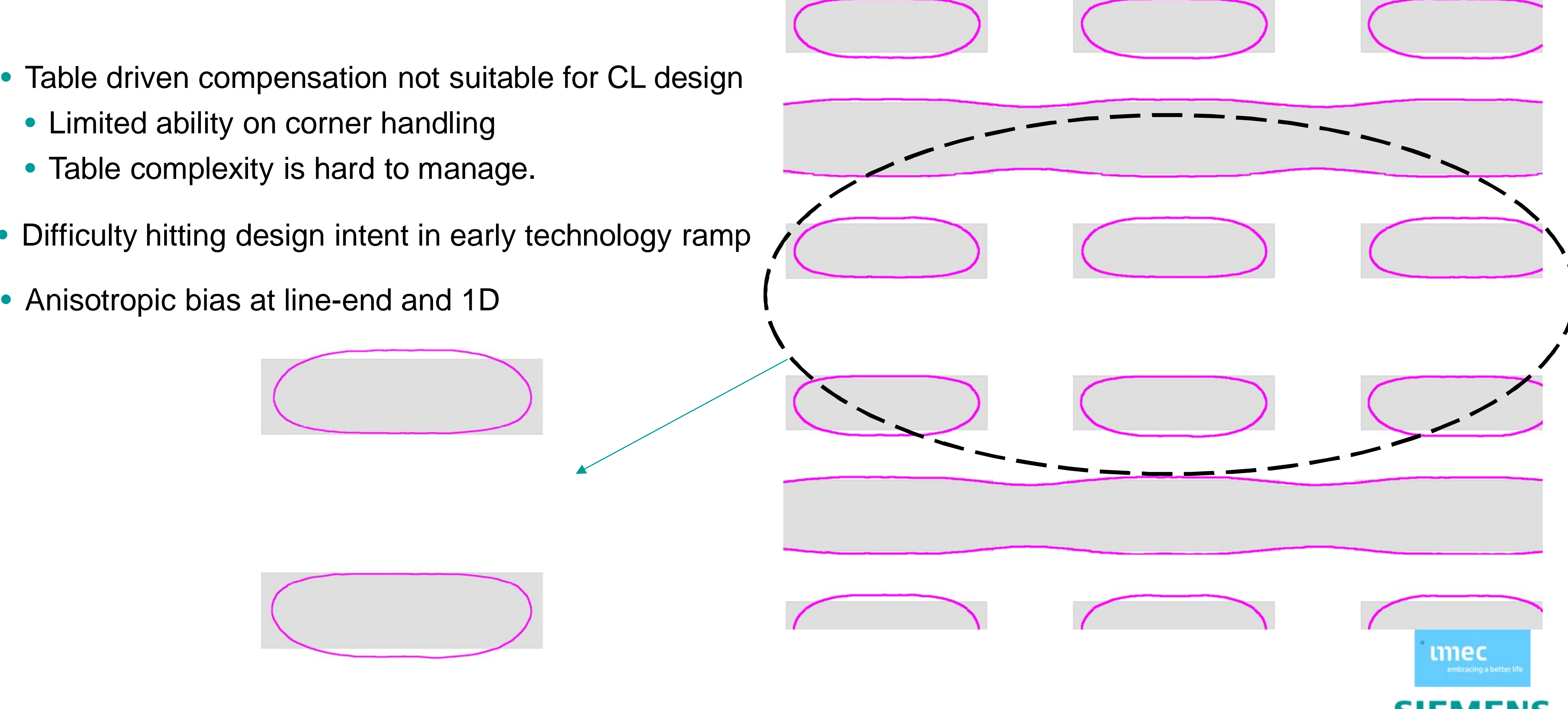


Curvilinear Biasing

- Rule-based biasing/retargeting for curvilinear design
- Gradual fragment smoothing

Typical CL ADI -> AEI Pattern Transfer Challenges

- Table driven compensation not suitable for CL design
  - Limited ability on corner handling
  - Table complexity is hard to manage.
- Difficulty hitting design intent in early technology ramp
- Anisotropic bias at line-end and 1D



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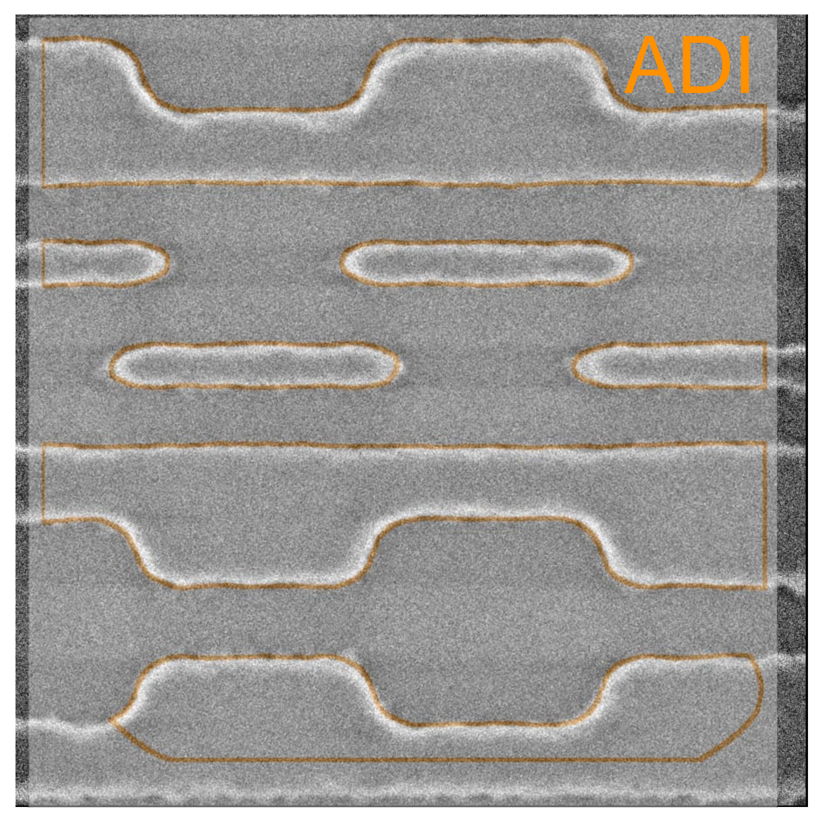

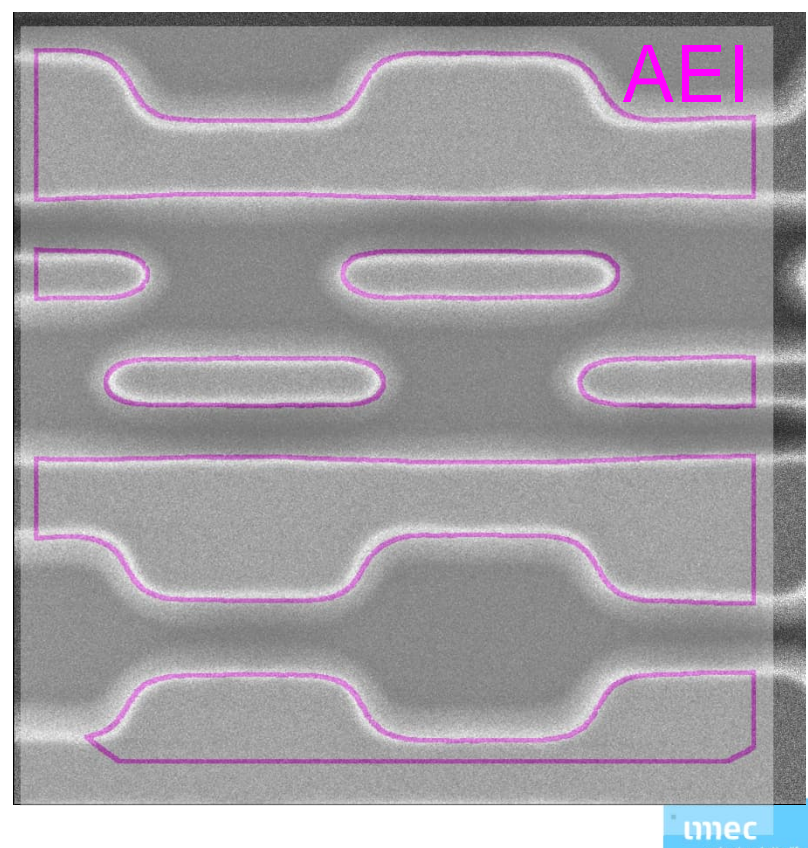

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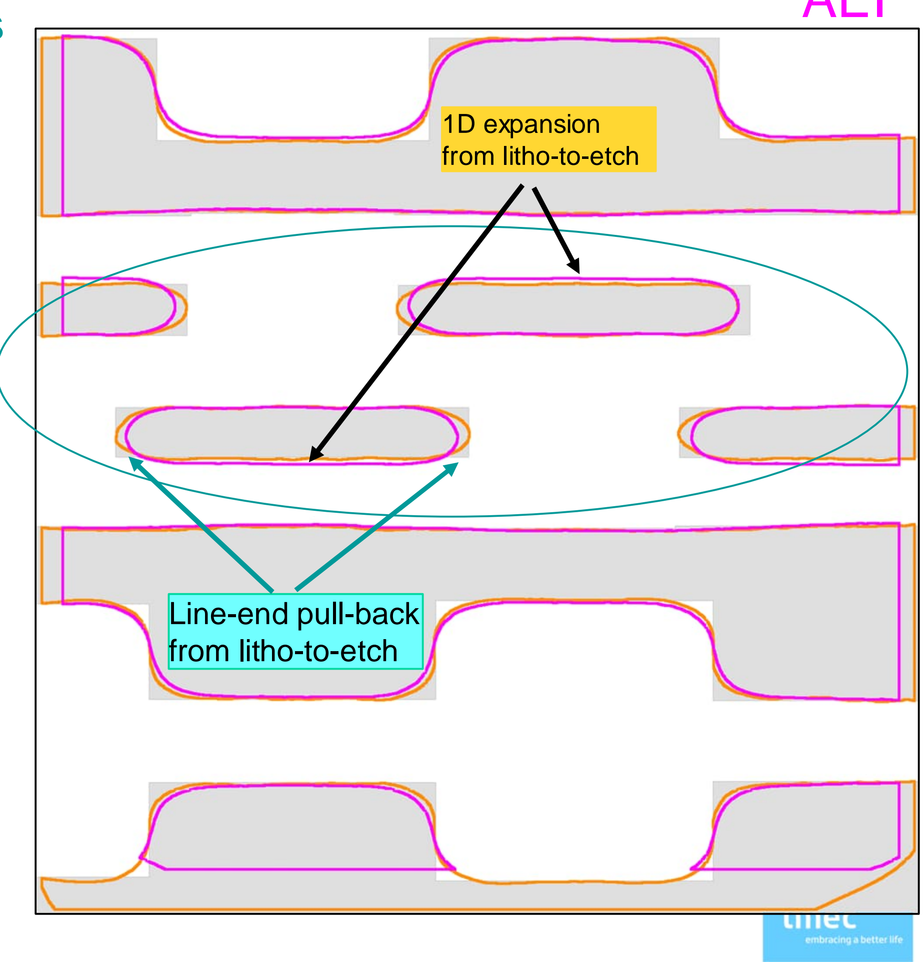
ADI
AEI



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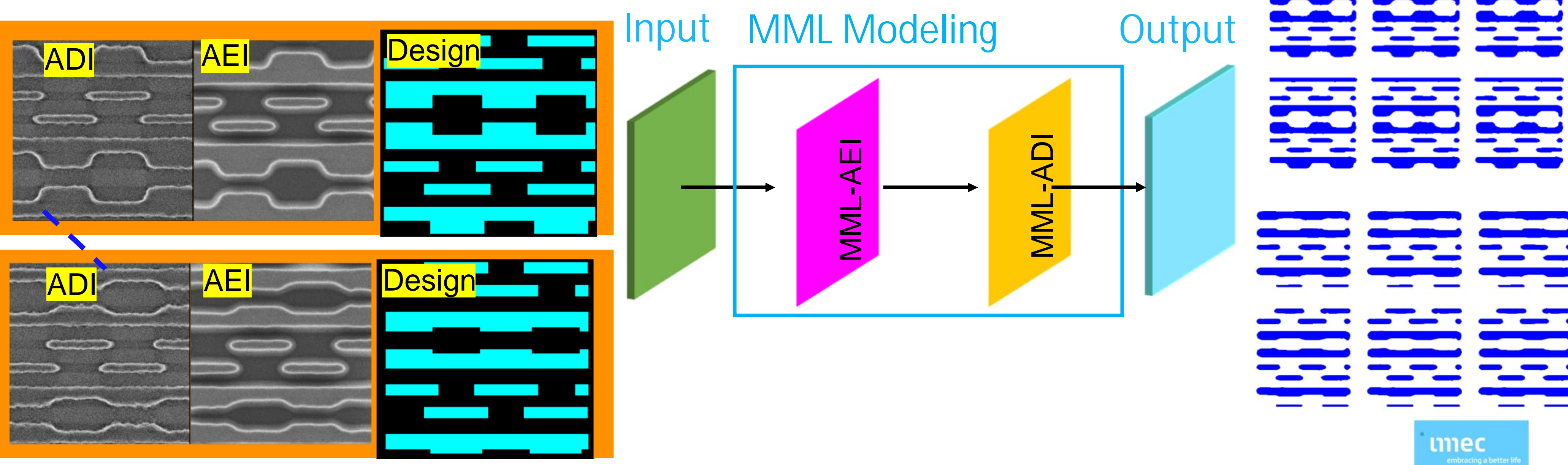
Goal: Derive the Litho Curvilinear Target Using SEM ADI and AEI Contours

- Instead of a single gauge, many more useful contours can be measured and used for modeling the litho retargeting
  - Increase throughput and efficiency
  - Reduce overall costs



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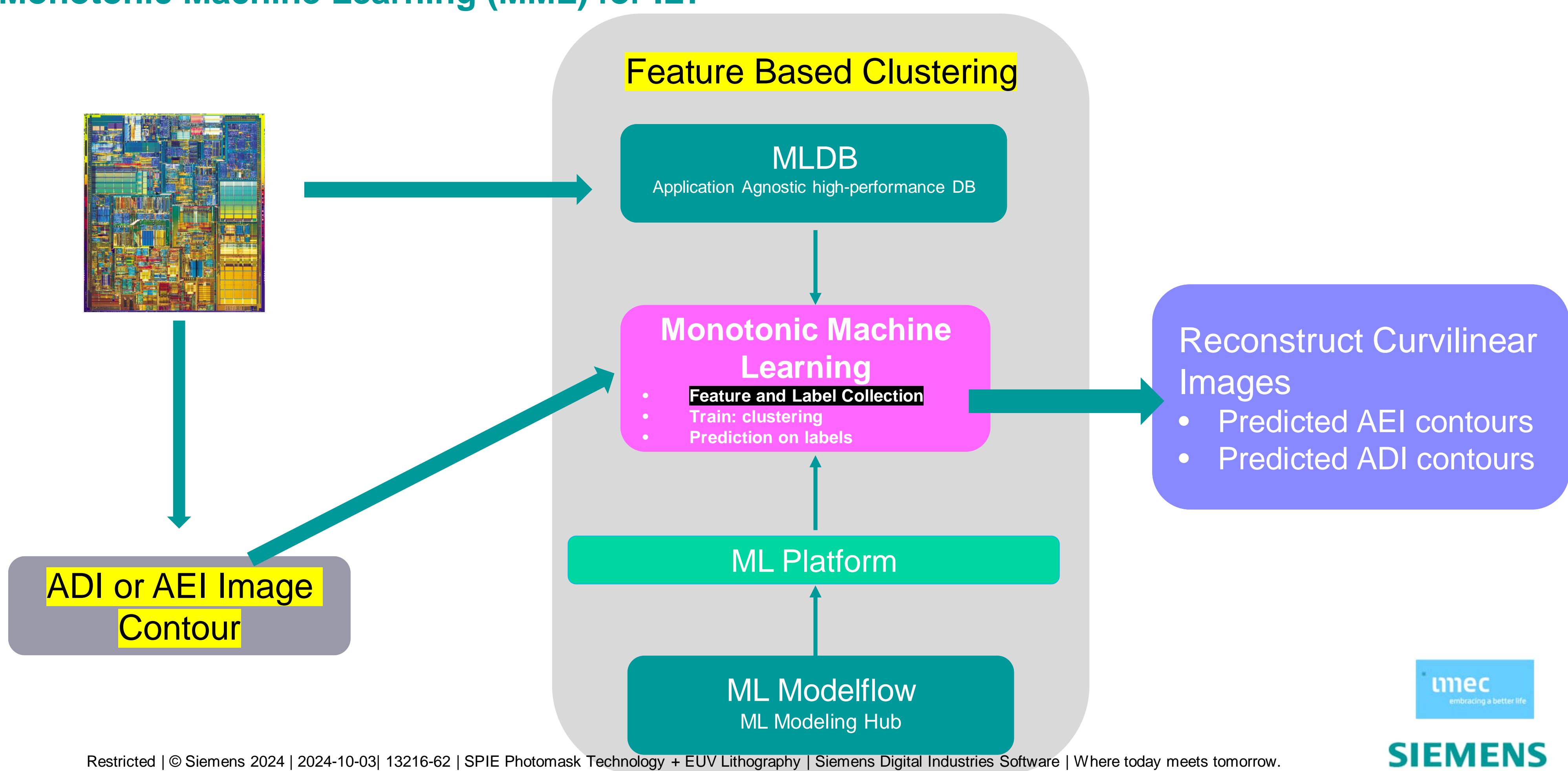
Monotonic Machine Learning (MML) for ILT



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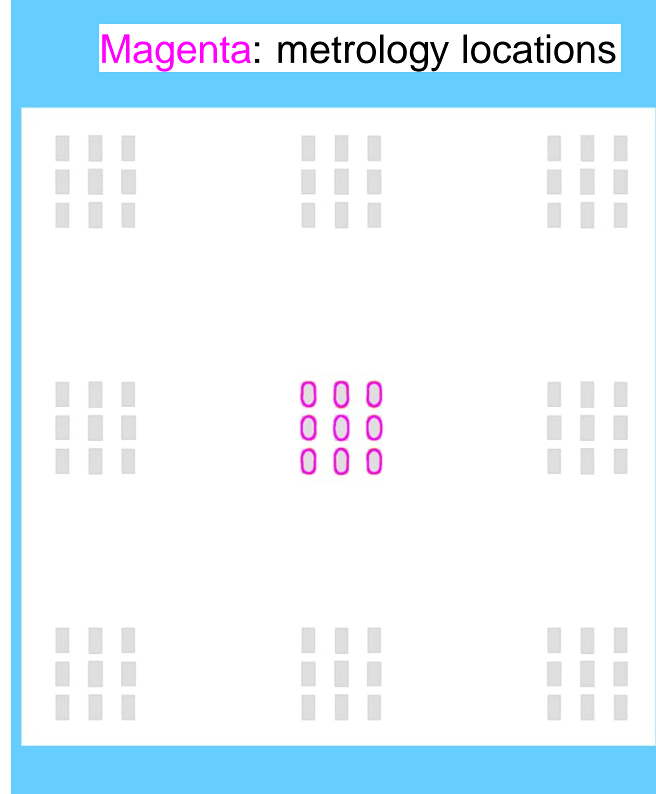
Test Pattern Design
Metrology Locations on wafer

Overview of the Test Case for MML Modeling: Design and Metrology

- What we have for MML modeling
  - Design:
    - Test patterns for an active layer a 28nm
  - Metrology Data:
    - ADI Image
    - AEI Image
    - ADI/AEI image contours overlaye with test patterns on GDS



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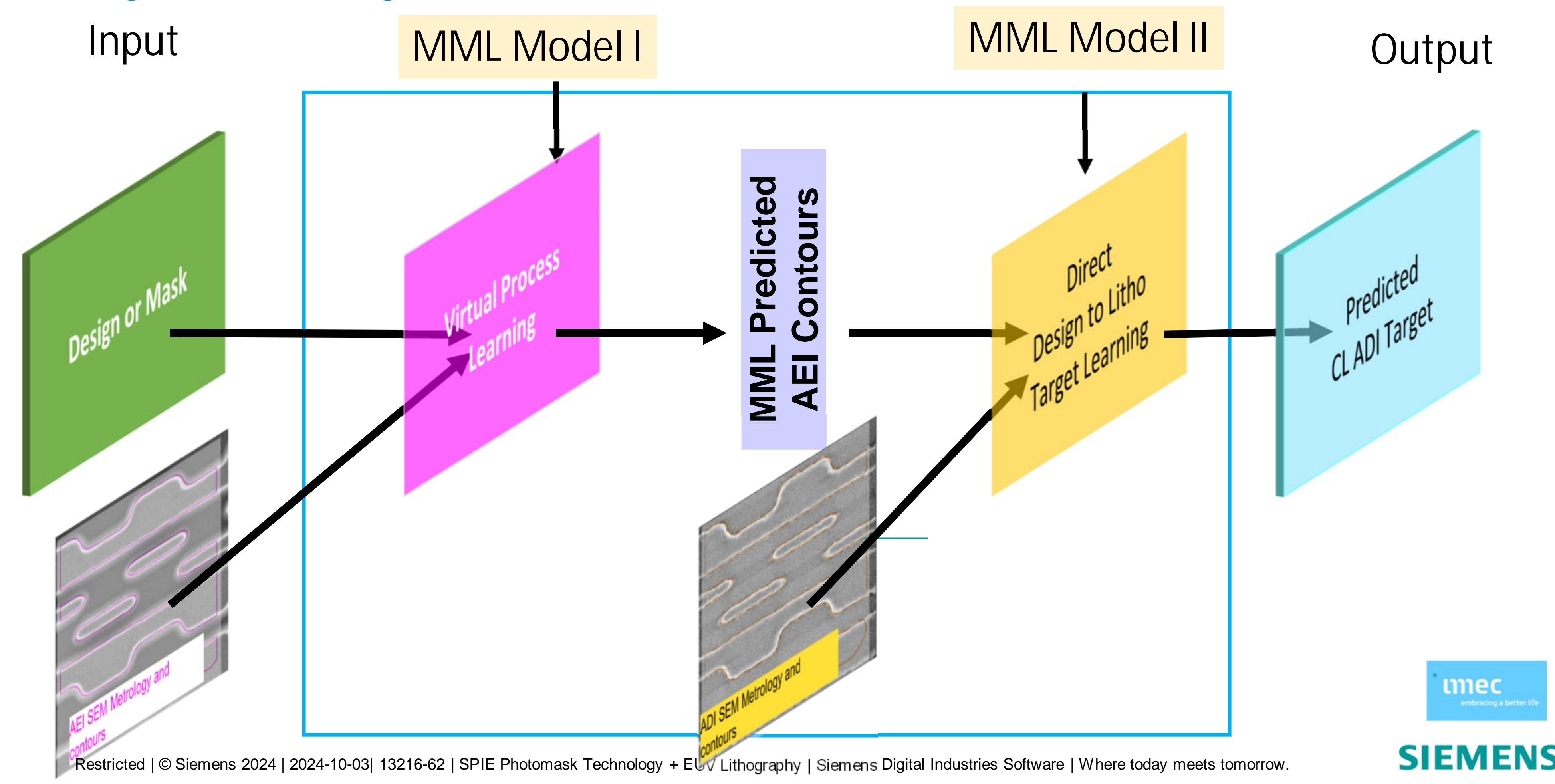
Dual stage MML Training Flow

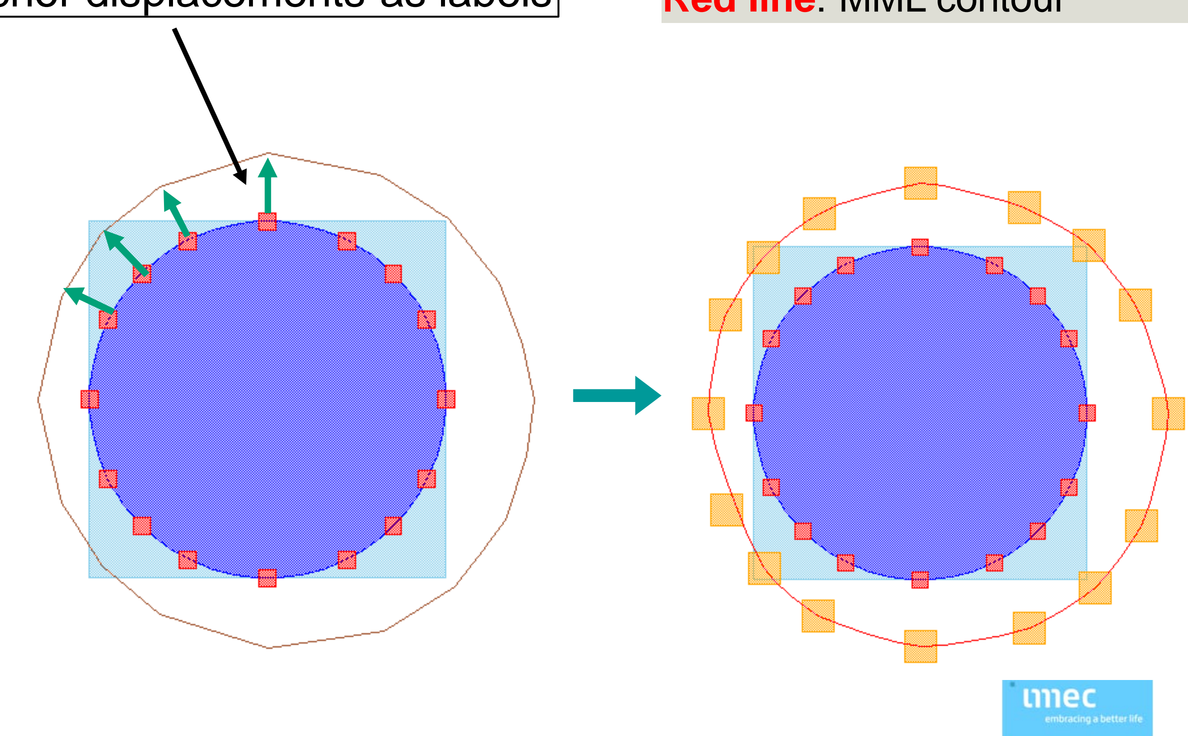


Light Blue: Design target
Brown: ADI contour
Blue: AEI contour
Red box: anchor point
Orange: replaced anchor point
Red line: MML contour

MML ADI/AEI Image Contour: Predict on Anchor Point Displacement

Feature Vector and Label Collection

- Collect Optical terms
  - 16 optical terms are used
- Collect Density terms from design target layer
  - Total of 44 features
  - Halo ranges from 0 to 1100nm in 4 directions
- Return Displacement from input target, draw contour



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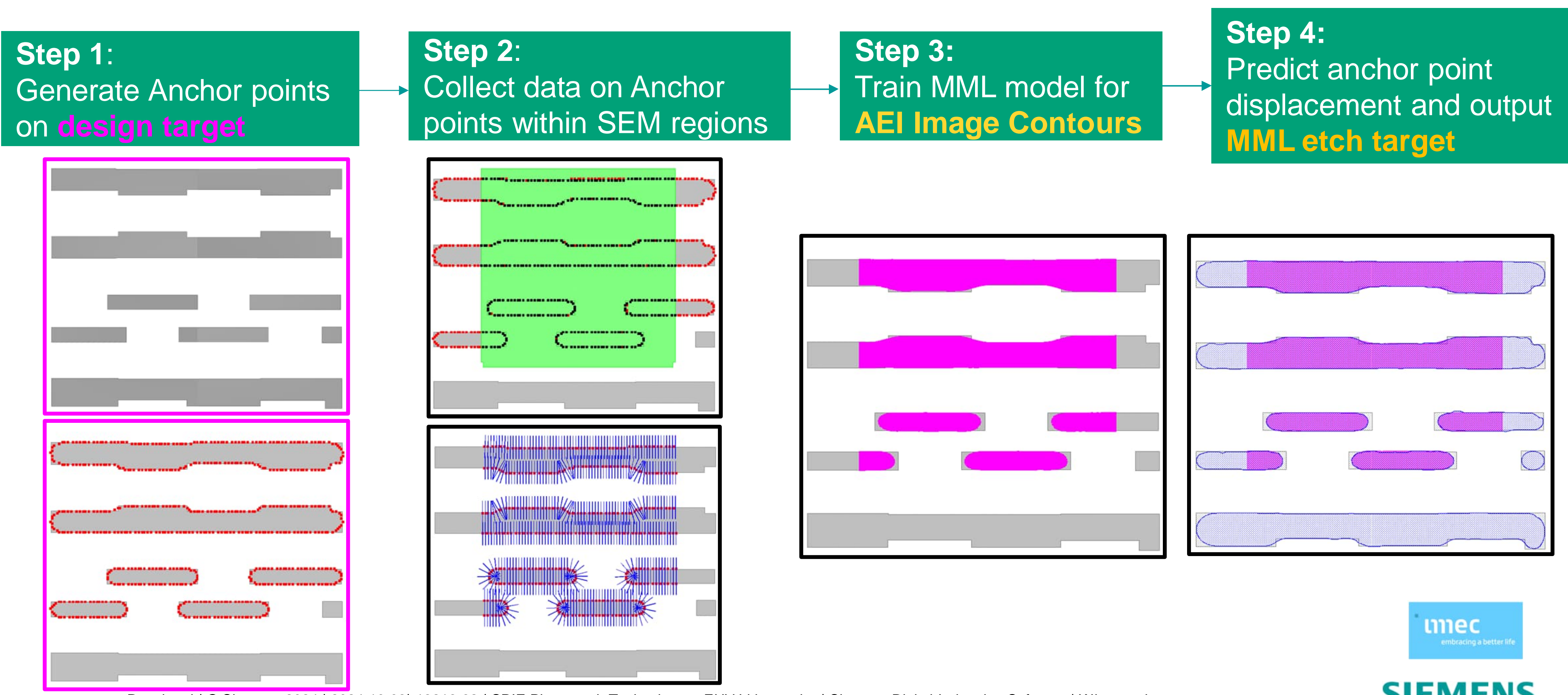
Dual Stage MML-Model Training Flow (I): Virtual Process Learning of Etch-Target from Design to Etch



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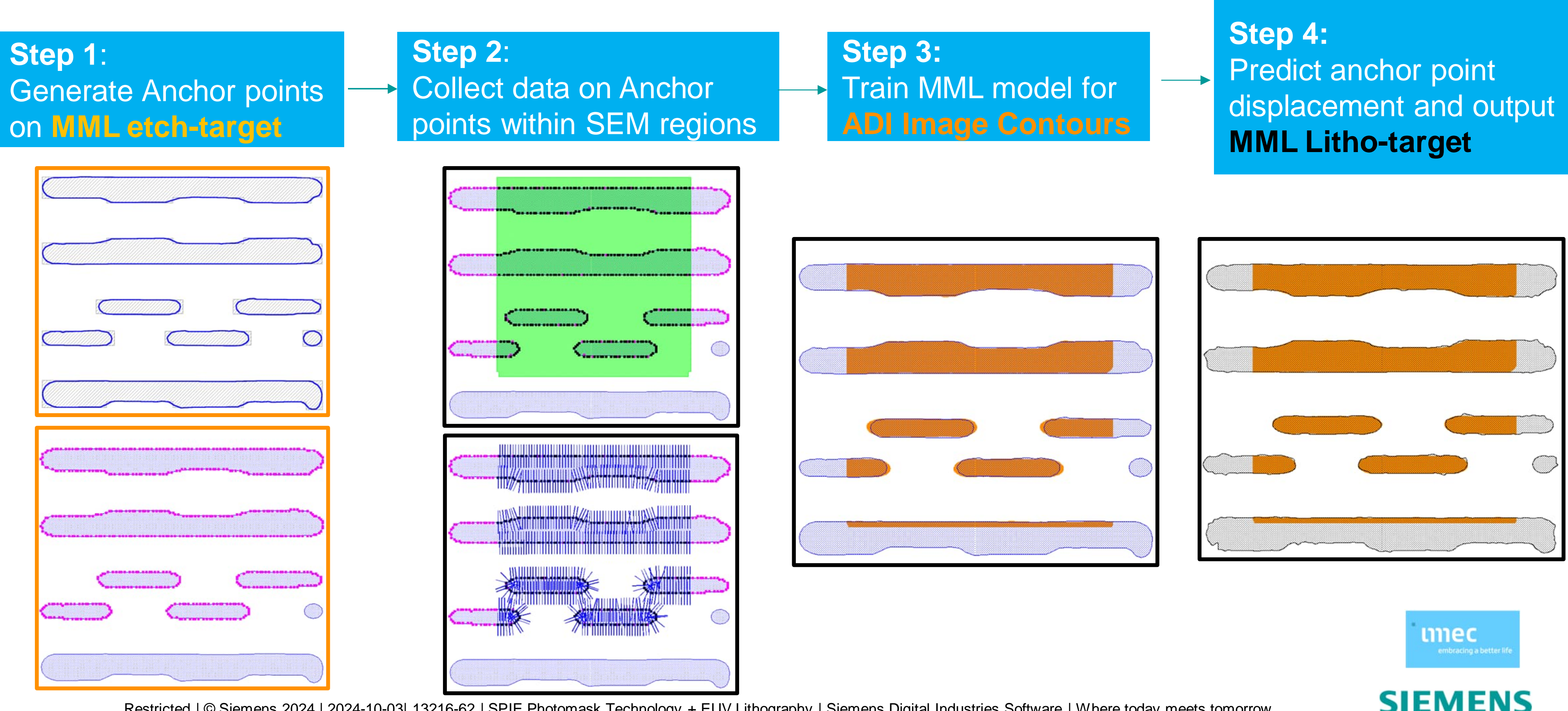
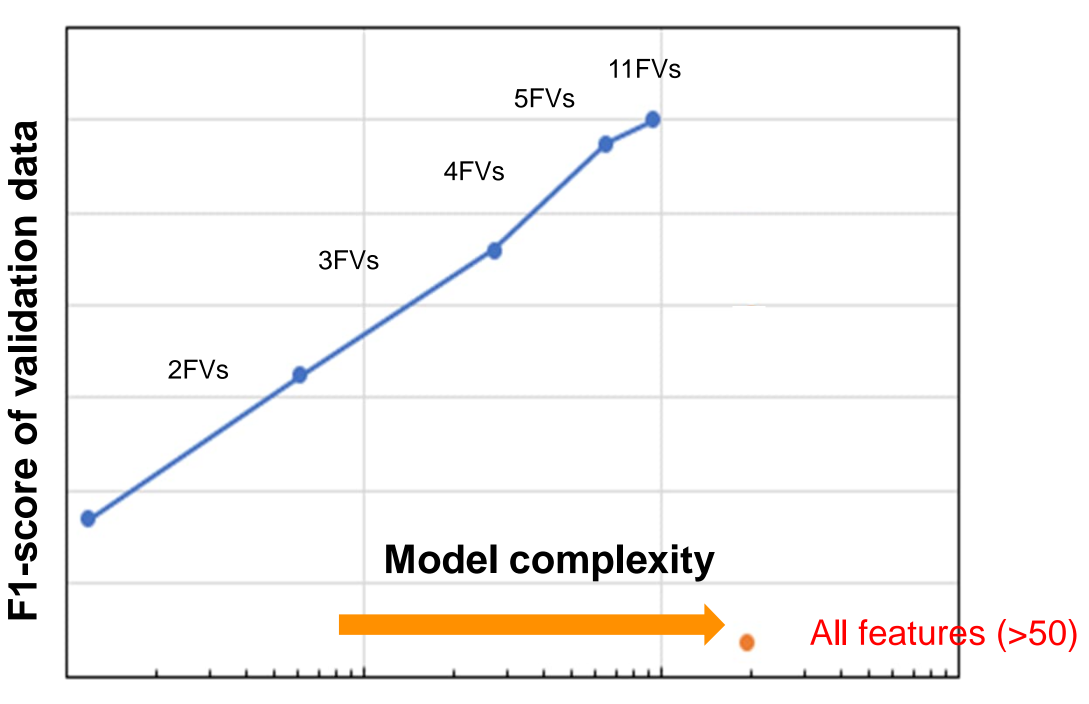
Dual Stage MML-Model Training Flow (II): Direct Design to Litho Target Learning



Feature Engineering

- Important features for MML for **virtual process learning**
  - Density halos:
    - 100nm to 500nm
    - 1 um: Long range effect from etch
- Important features for **MML direct design-to-litho target learning:**
  - Density halos:
    - 100nm and 200nm



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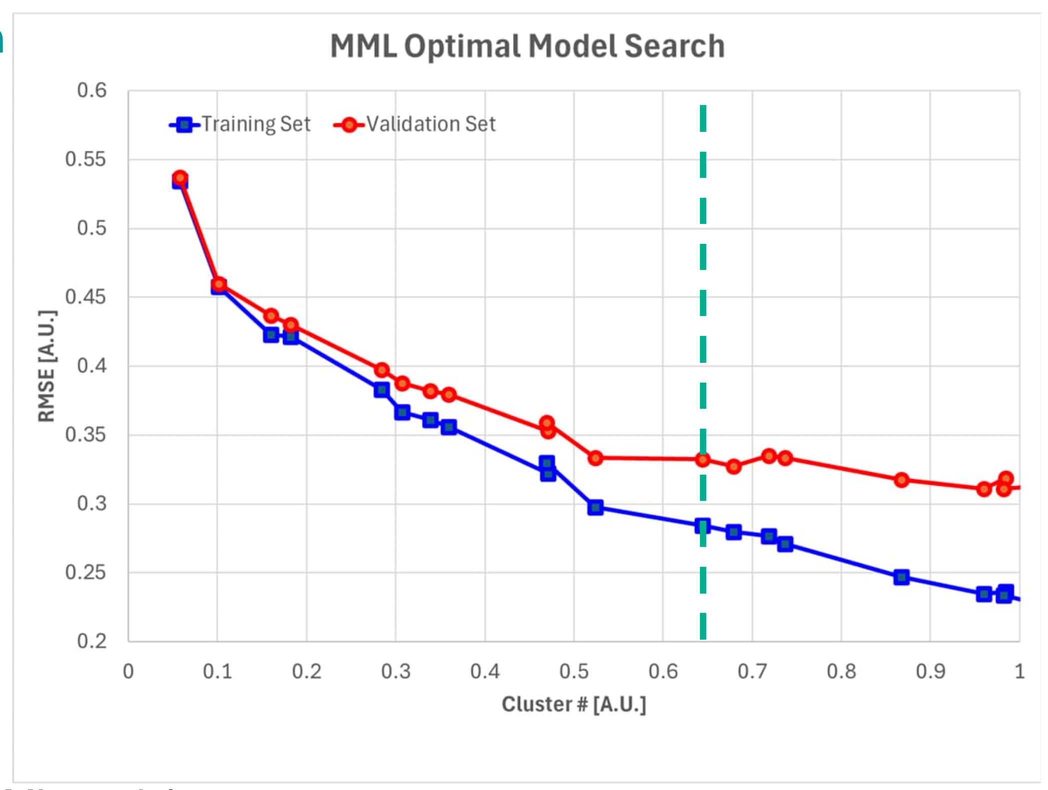
Optimal MML Model Search



- Searching the optimal MML model
  - The training dataset (80%) is used to build a model with the target clusters
  - The model is then applied to a validation dataset (20%) for assessment
- The optimal cluster #is selected when the RMSE of the validation dataset starts to increase

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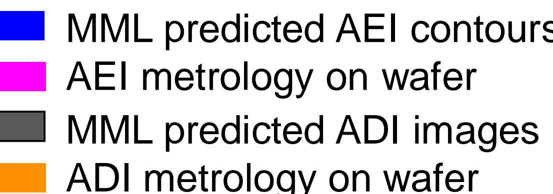
Virtual Process Prediction: MML Predicted AEI Images

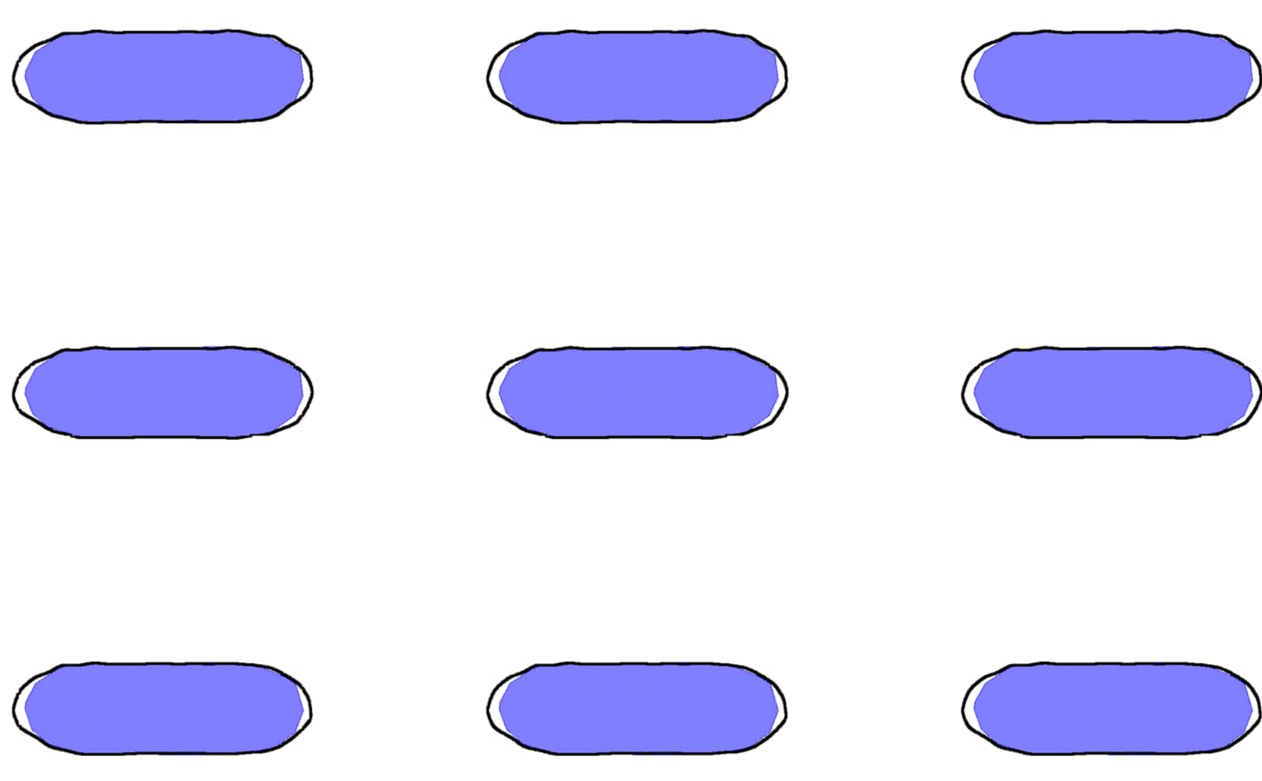
Virtual Process Prediction: MML Predicted AEI Images

Direct Design-to-Target: MML Predicted ADI Images

Direct Design-to-Target: MML Predicted ADI Images

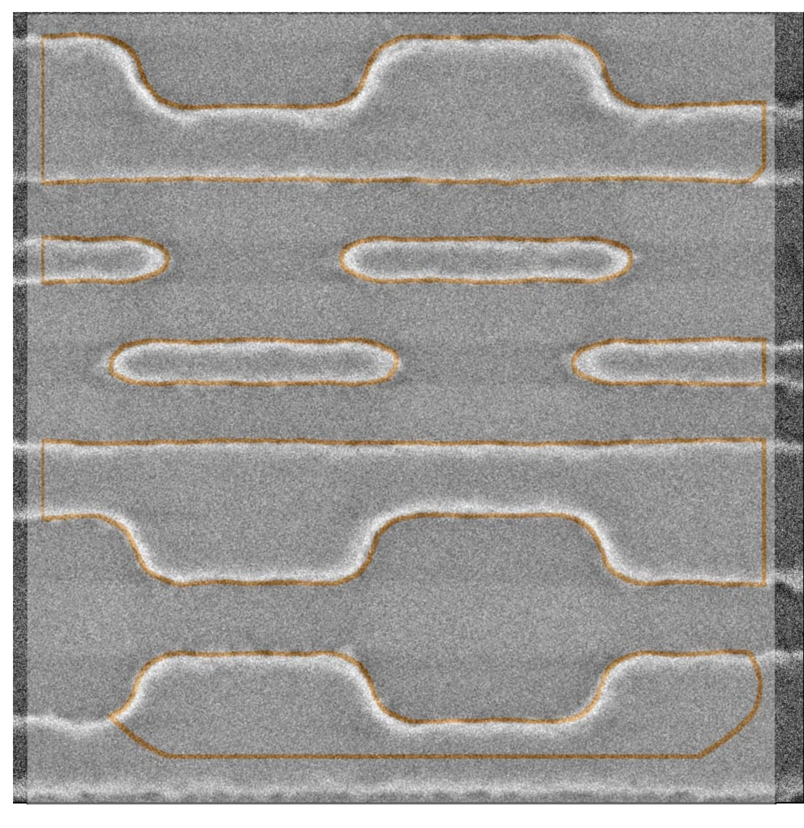
MML Predicted AEI Vs. ADI

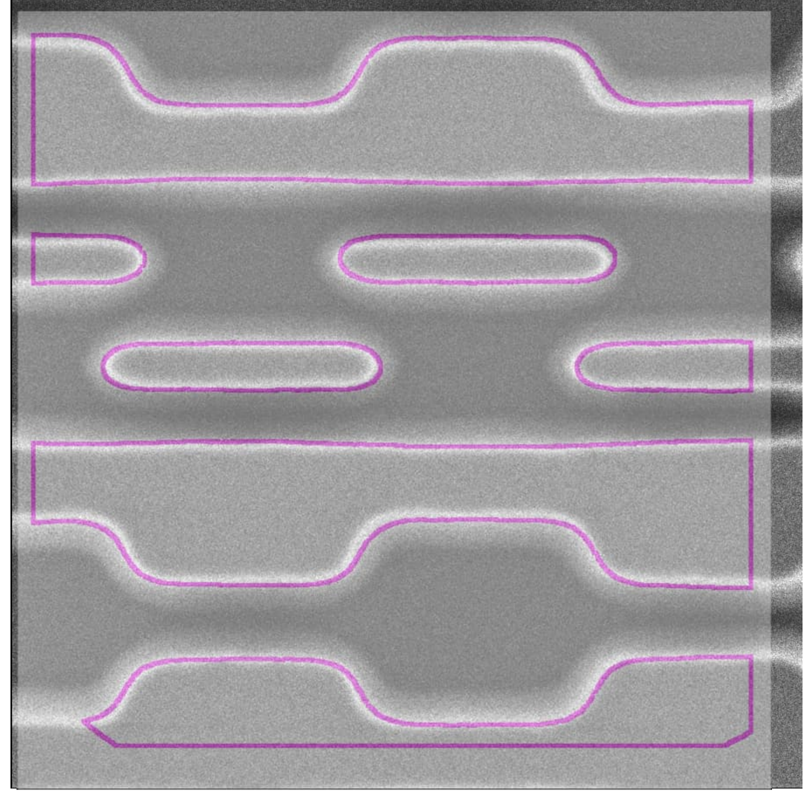




MML Prediction on Etch Bias on Line-End and 1D (I): ADI and AEI Metrology Contours

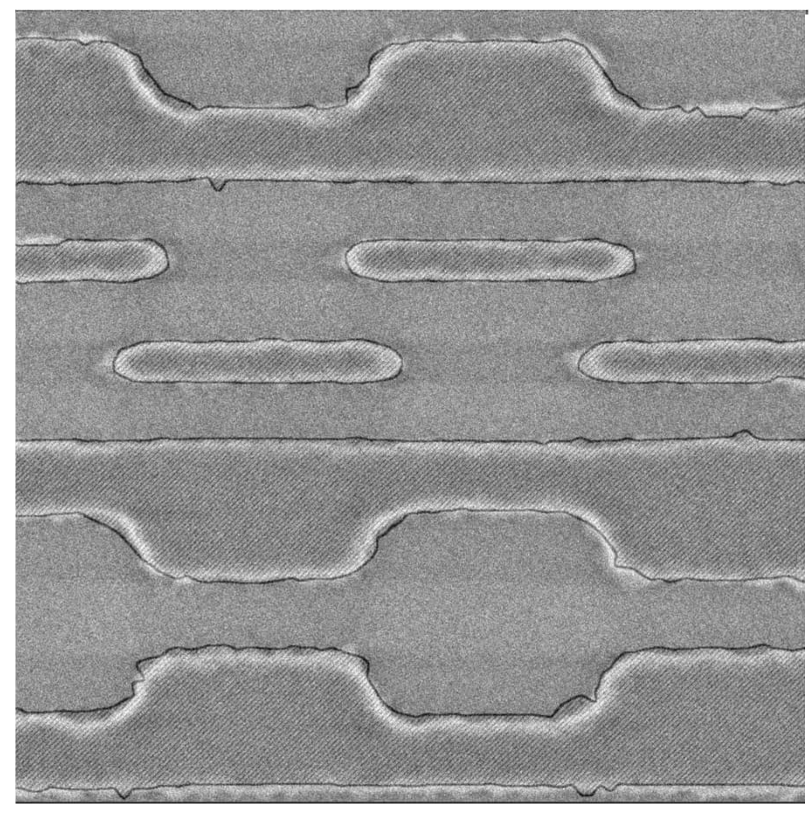
AEI metrology on wafer
ADI metrology on wafer

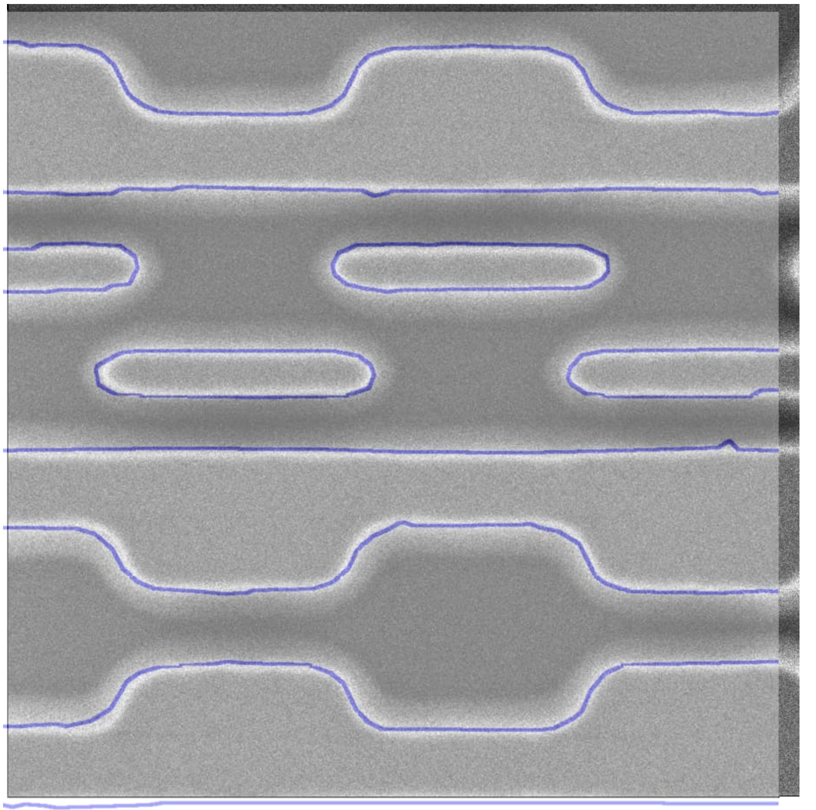




MML Prediction on Etch Bias on Line-End and 1D (II): MML Predicted ADI and AEI Contours

MML predicted AEI contours
MML predicted ADI contours





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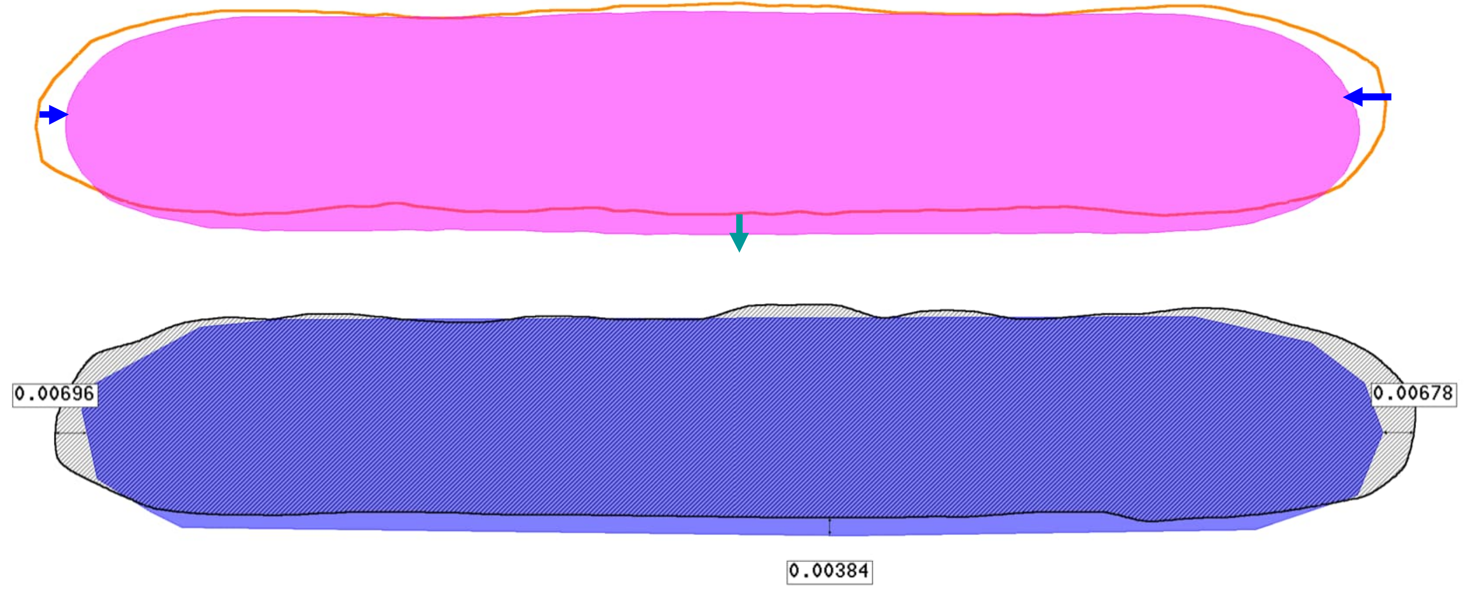
MML Prediction on Etch Bias on Line-End and 1D

Observations from litho to etch:

- Line-end pulls back
- 1D edge on bottom expands



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Summary

- Monotonic Machine Learning (MML) is a machine learning solution to learn any curvilinear contours
- MML curvilinear target generation is done by training and predicting the displacements of spline anchor points with respect to the reference contours e.g. ADI and AEI SEM contours
  - Anchor points are directly moved for the SEM contour shape, giving a curvilinear correction
- Implemented feature engineering and showed that the maximum halo range for AEI is 1um for this small test case
- The optimal MML models are searched for both MML models for ADI and AEI
  - 80% for training and 20% for validation
- Successfully predicted both AEI and ADI contours with test patterns of an active layer by using limited amount of AEI and ADI images
  - The asymmetrical etch biases observed for line-end and 1D line are captured

THANK YOU