New Trends in Computational Lithography – Data, Algorithms, and Applications

Yu Cao

ASML-Brion

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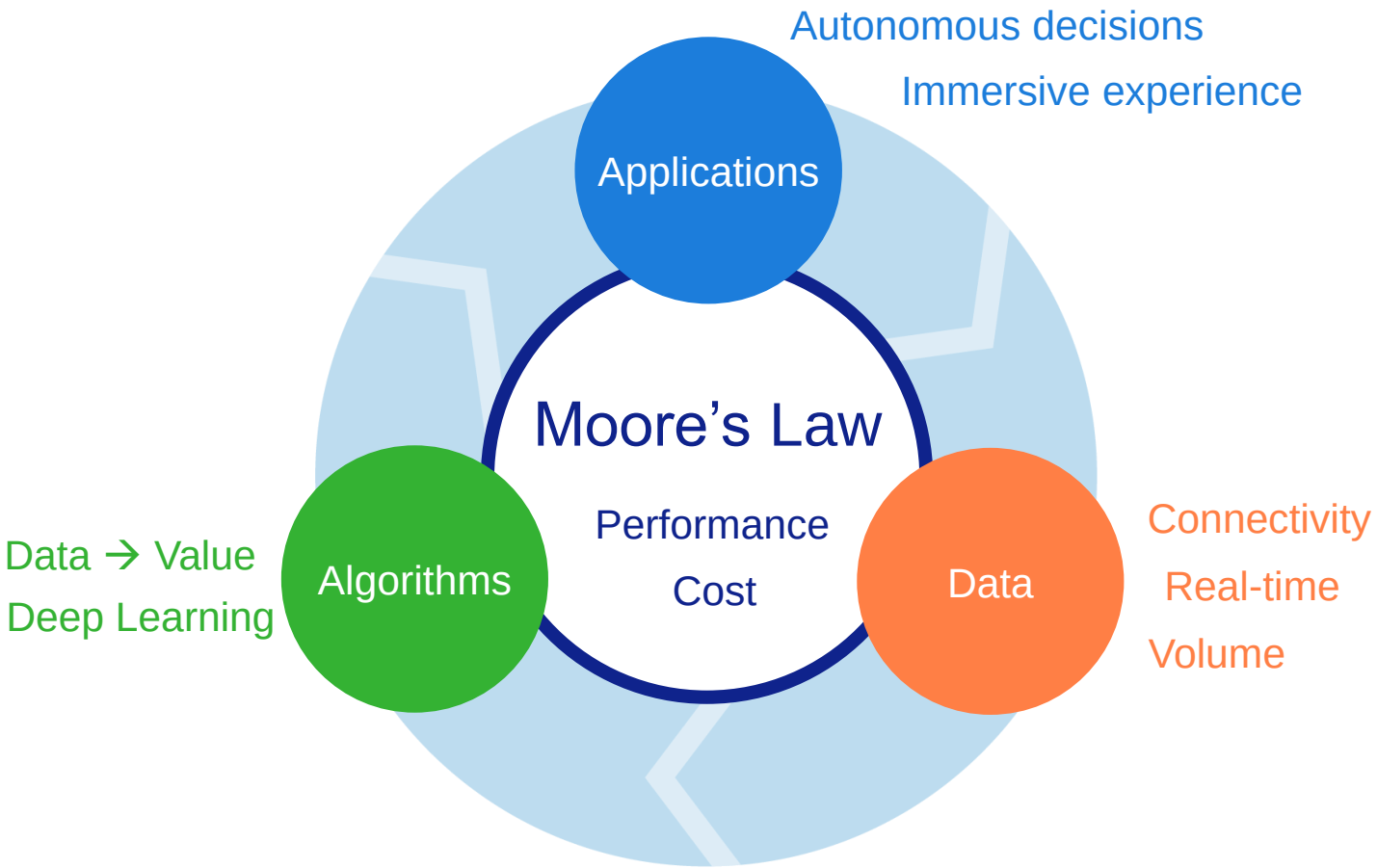
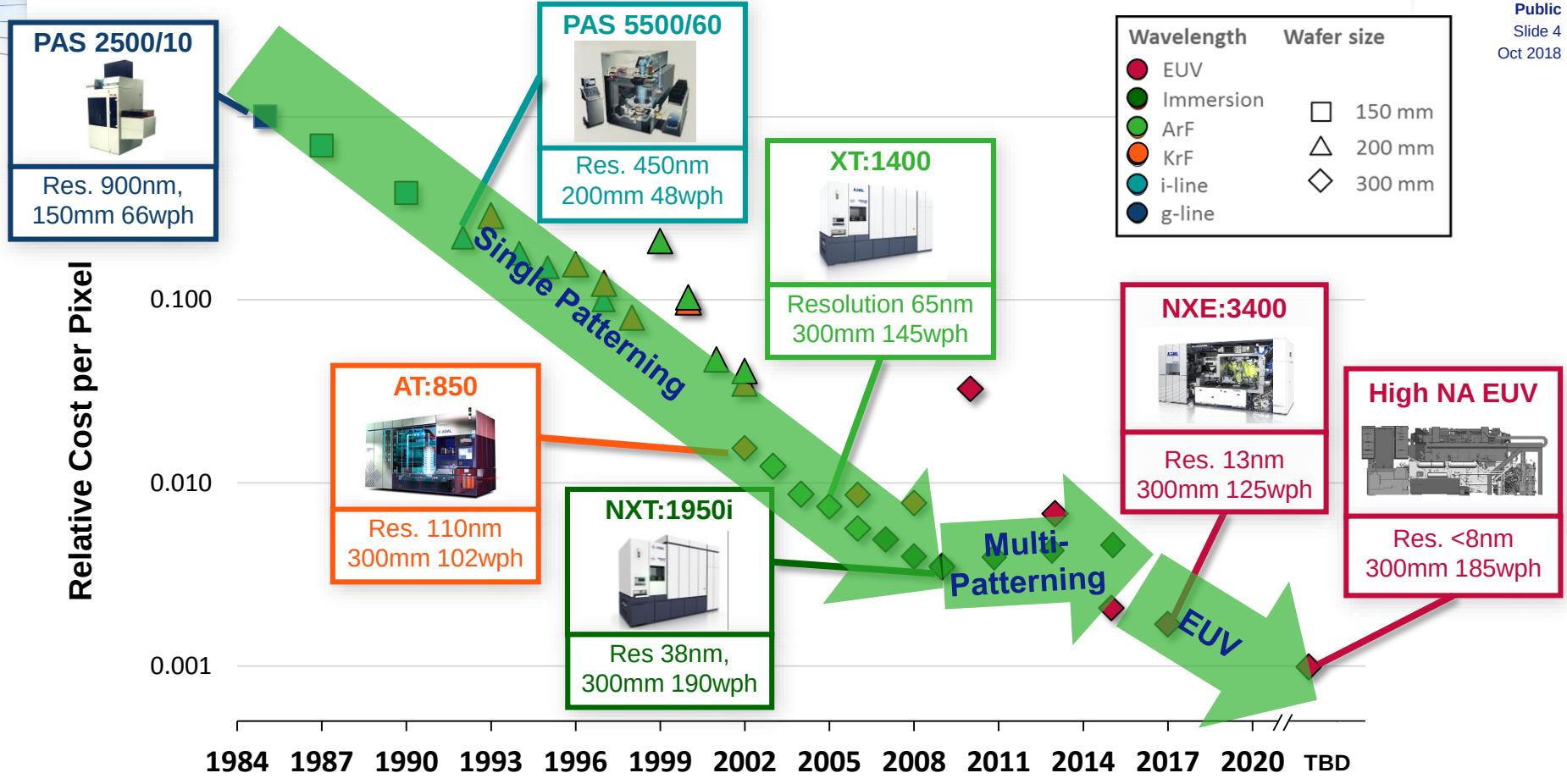
Outline

- New challenges arise in ***accuracy*** and ***speed*** to meet demands in 7nm and beyond
  - Accuracy requirements are approaching single nanometer
  - Worldwide computing power for OPC has exceeded 10 PFLOPS, on par with the world's most powerful supercomputers and incurring substantial cost
- New opportunities enabled by new technologies:
  - New ***data*** acquisition by fast e-beam metrology systems
  - New ***algorithms*** for modeling and optimization further empowered by machine learning and new computing architecture
  - New ***applications*** in patterning equipments including EUV scanners and multi-beam mask writers

Major trends in semiconductor-enabled computing



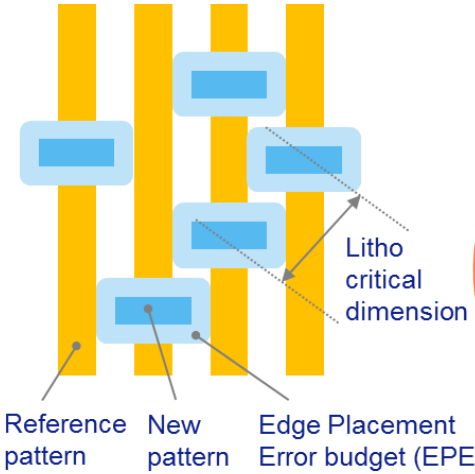
Litho cost reduction continues to drive Moore's Law



Scaling requires Edge Placement Accuracy improvements

ASML has expanded its focus to address the total litho error

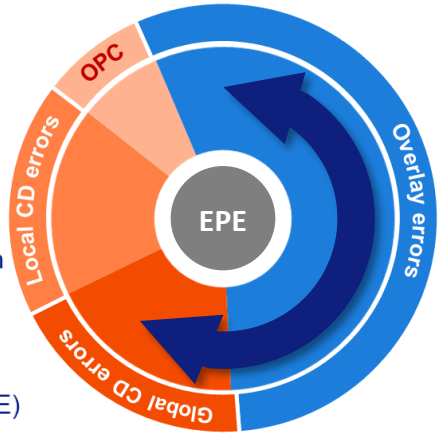
Device Pattern



Edge placement errors result from a combination of Overlay and CD patterning errors.

2005 65nm Node

XT:1400, ArF, NA 0.93
Single Expose, k_1 0.43

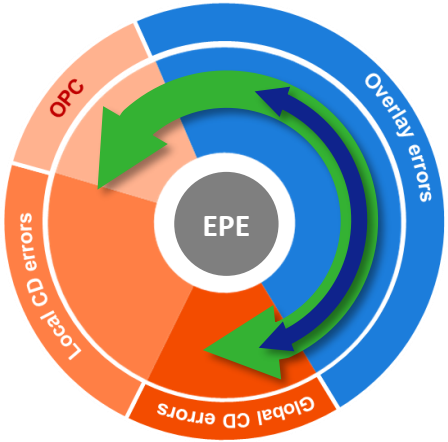


Scanner

>50% of EPE budget

2011 28nm Node

NXT:1950i, ArFi, NA 1.35
Single Expose k_1 0.28



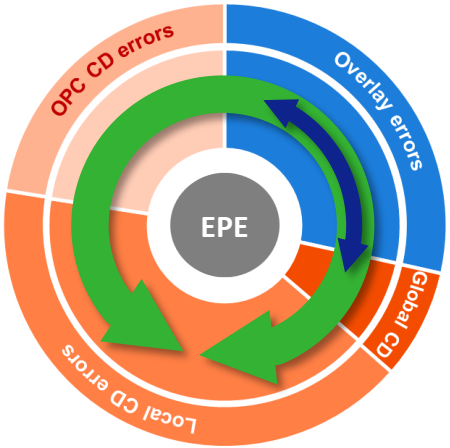
Holistic Lithography

- Brion Computational Litho & OPC
- YieldStar Optical Metrology
- Scanner Feedback and Control

>75% of EPE budget

2019 5nm Node

NXT:2000i-NXE:3400 ArFi-EUV
Multiple Patterning k_1 0.1 - 0.5



Pattern Fidelity Control

- HMI e-beam metrology & inspection
- YieldStar extension post etch, in-die
- Litho-Etch co-optimisation

>90% of EPE budget

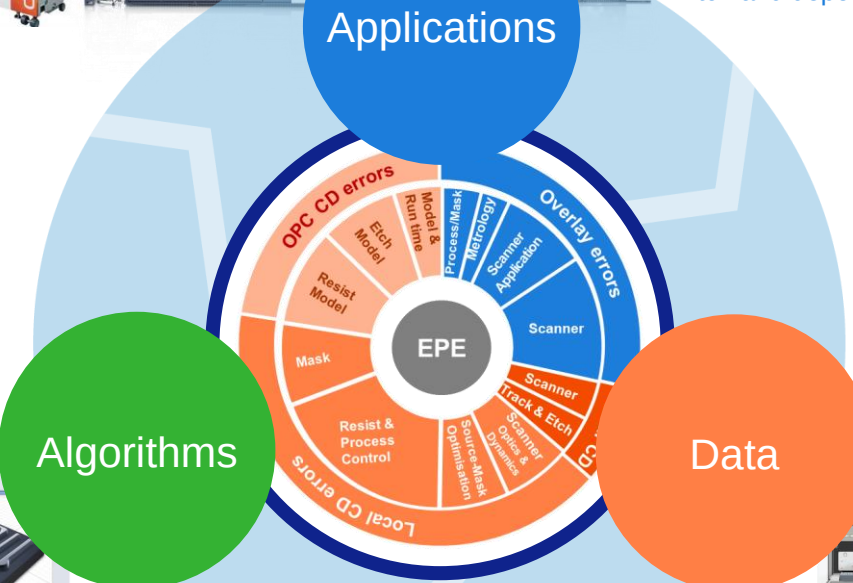
ASML contribution

CD: Critical Dimension, OPC: Mask Optical Proximity Correction

Holistic Lithography delivering significant customer value

Lithography scanner with advanced control capability

Etch and deposition tools



Computational lithography and metrology

Optical and e-beam metrology

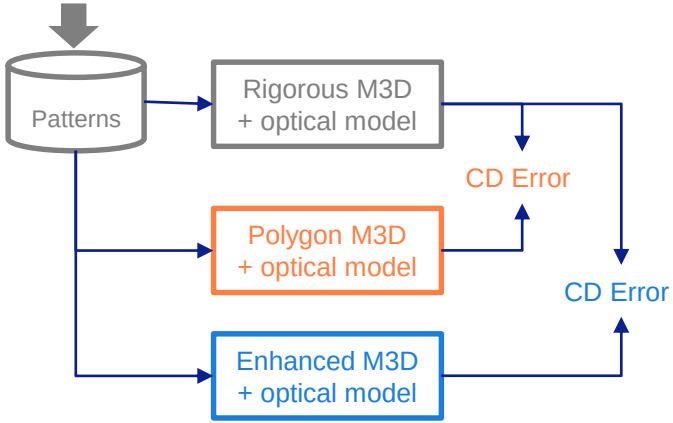
Tachyon model products extend model accuracy roadmap toward single nanometer

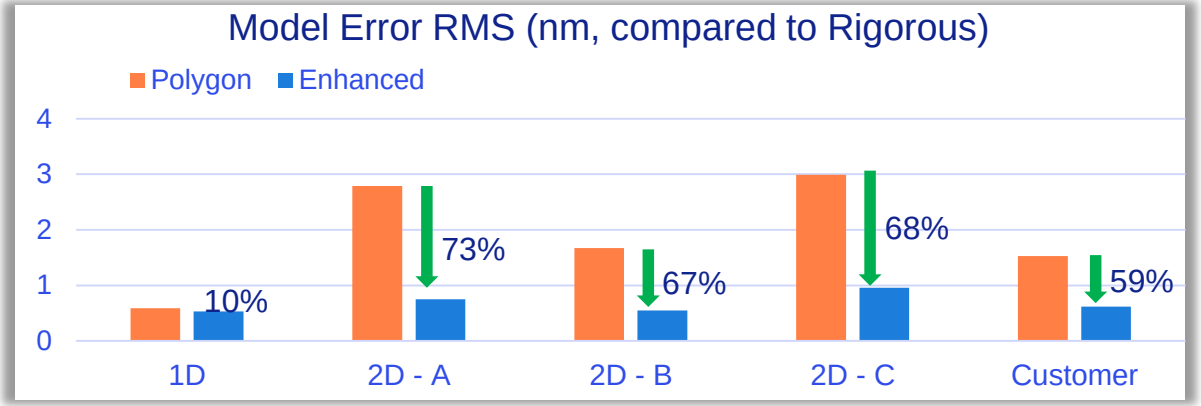
		2017	2018	2019	2020	2021
Accuracy	EPE Roadmap (max EPE)	9 nm		7.5 nm		5 nm
	ADI Model accuracy (CD 3σ)	**2D: 2.5 nm**	2D: 2.2 nm	**2D: 1.8 nm**	2D: 1.5 nm	**2D: 1.2 nm**
Physical based Models (Tachyon FEM+)	Mask	enhanced M3D (eM3D) model for 2D patterns		eM3D model for DUV curvilinear masks	eM3D model for EUV curvilinear masks	eM3D model for HiNA EUV
	Post Exposure Bake (PEB)	Higher order PEB terms (xPEB)	EUV PRS (speed up etc)	2D Stochastic modeling (SEPE)	EUV NTD & novel resists	HiNA EUV resists
	Development	Development Shrinkage (PRS+)	Surface Tension model & Physical resist development		EUV NTD & novel resists	HiNA EUV resists
	Etch	Effective Etch Bias Model (EEB)	Physics based etch model			
Newron Models using Machine Learning		NEWRON	Newron resist model	Newron etch model		Newron M3D model
Model Calibration with Massive Metrology			**eP5-MXP** ~1,000K CD/EP gauges		**eP5/ePx-MXP** >1,000K CD/EP gauges high performance contour based model calibration	

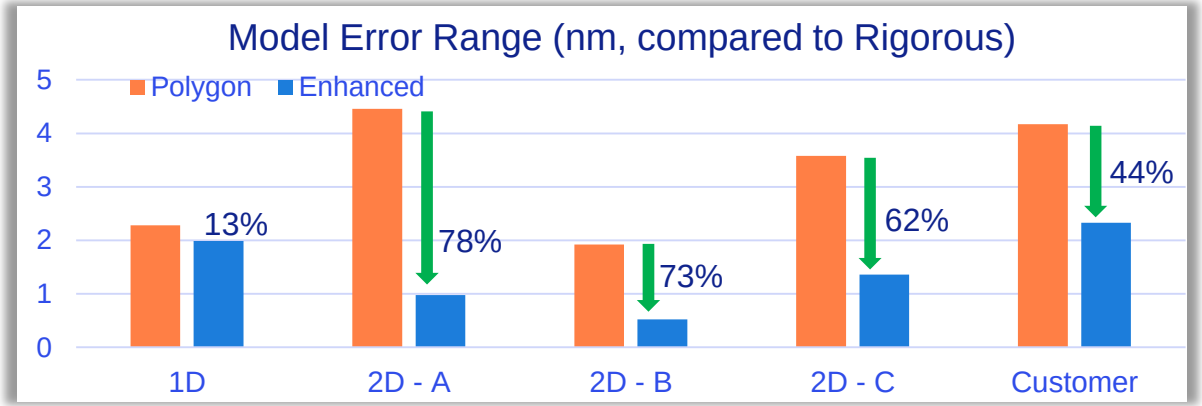
Enhanced 3D mask model delivers significant accuracy benefits

Selected DUV patterns:

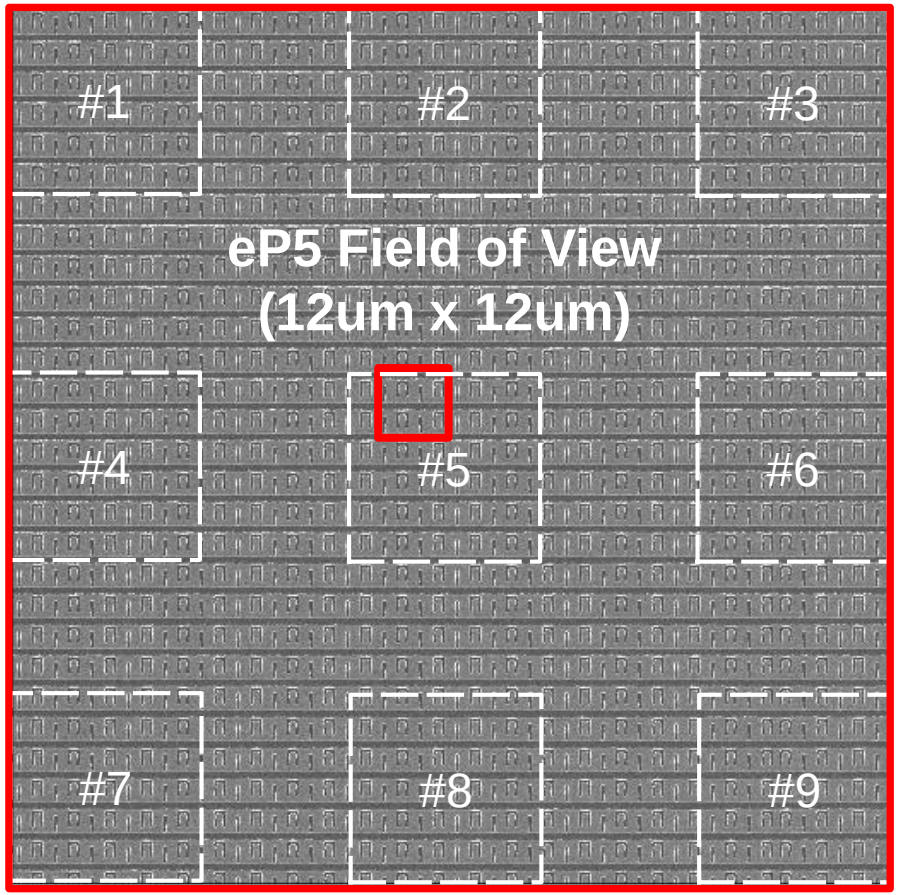
- 1D (82 gauges)
- 2D – A (15 gauges)
- 2D – B (9 gauges)
- 2D – C (9 gauges)
- Customer (48 gauges)



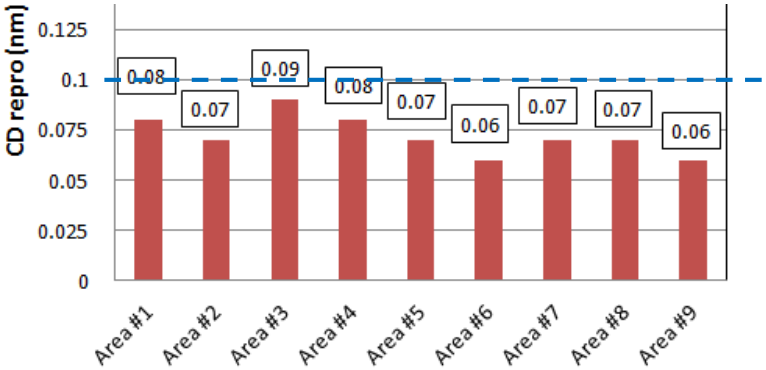




High speed e-beam metrology and large field of view

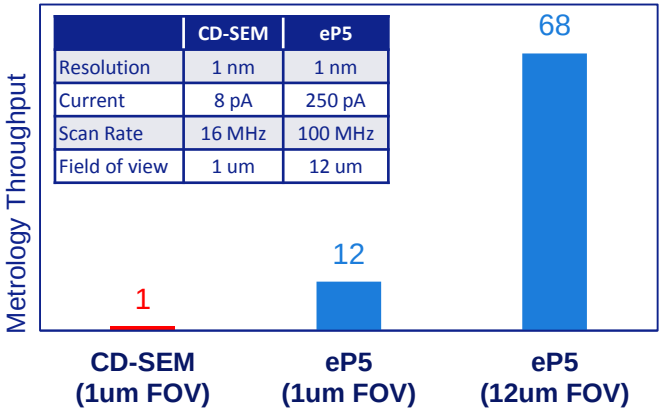


Excellent precision across large field of view



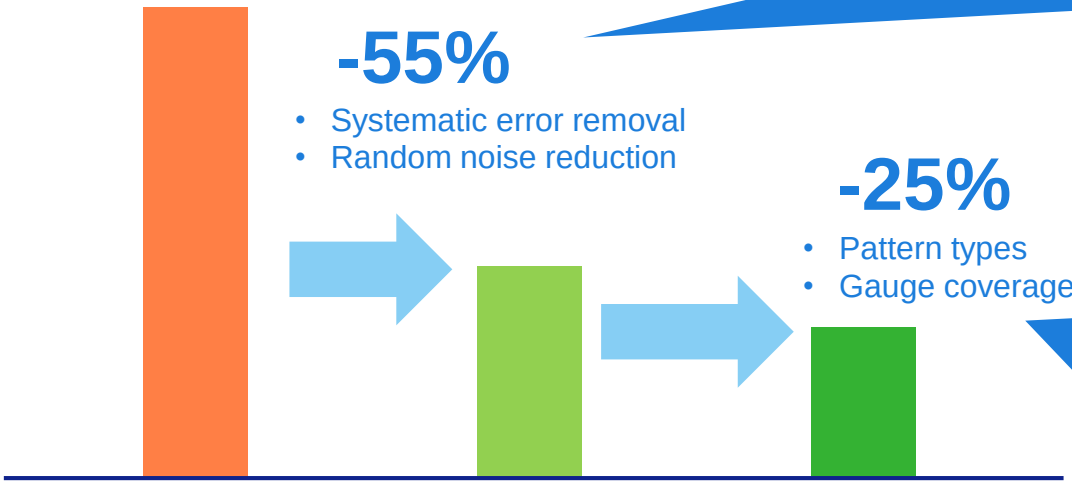
Throughput advantage over CD-SEM

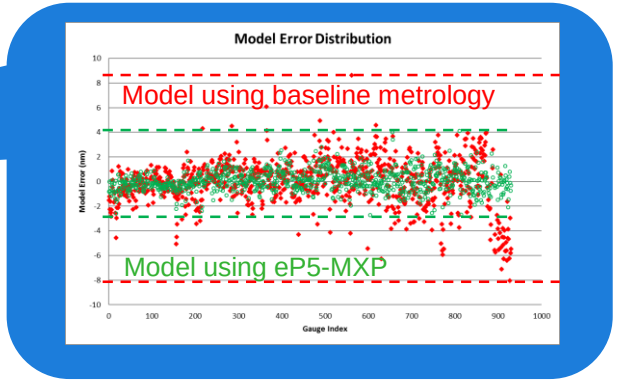
	CD-SEM	eP5
Resolution	1 nm	1 nm
Current	8 pA	250 pA
Scan Rate	16 MHz	100 MHz
Field of view	1 um	12 um

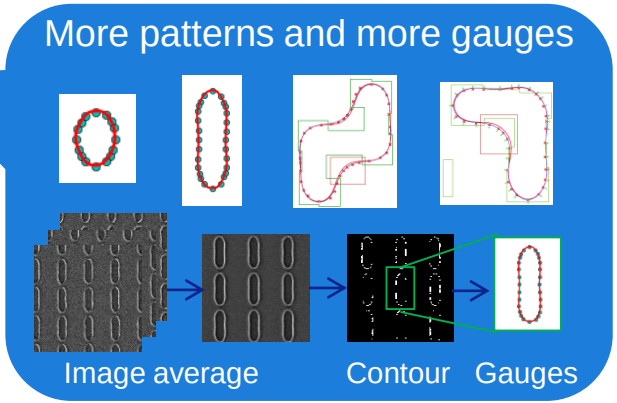


Fast e-beam enables massive metrology sampling

This improves OPC model accuracy and cycle time







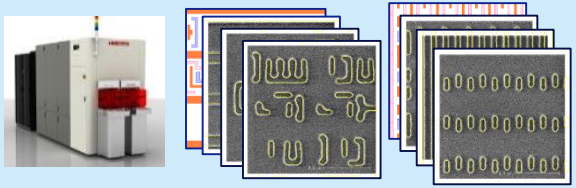
SPIE 2018, Qian Zhao et al – "Massive metrology using fast e-beam technology improves OPC model accuracy by >2x at faster turnaround time"

Better accuracy of resist models by machine learning

Enabled by fast e-beam metrology and physical based models

Accuracy

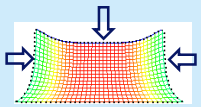
Data-driven **training** based on fitting spec and wafer measurements



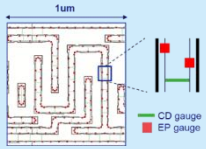
Large volume wafer metrology data, further enhanced by fast e-beam

Stability

Physical driven **training** using physics based lithography models



Physical Resist Shrinkage



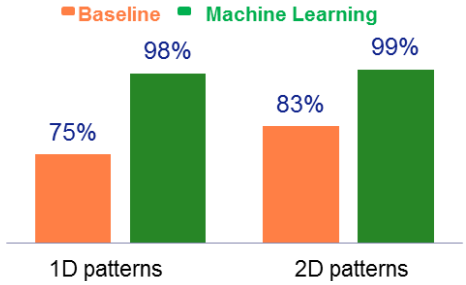
Data expansion through simulated contours

ASML Machine Learning model

Takes input from both wafer data and physics-based litho models to achieve better **accuracy** and retain **stability**

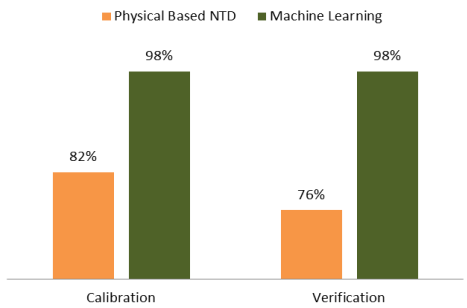
Example 1

Percentage of patterns within accuracy spec



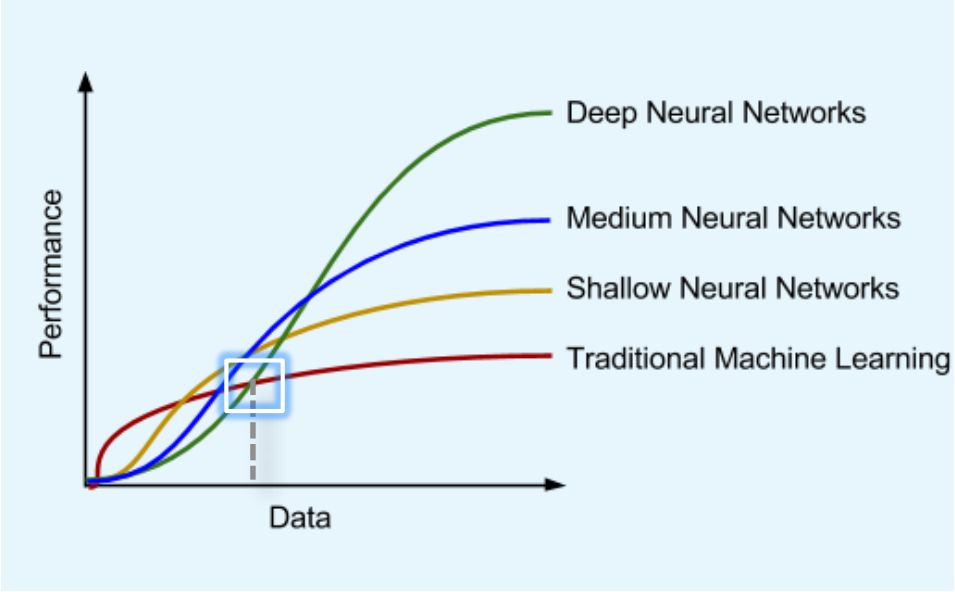
Example 2

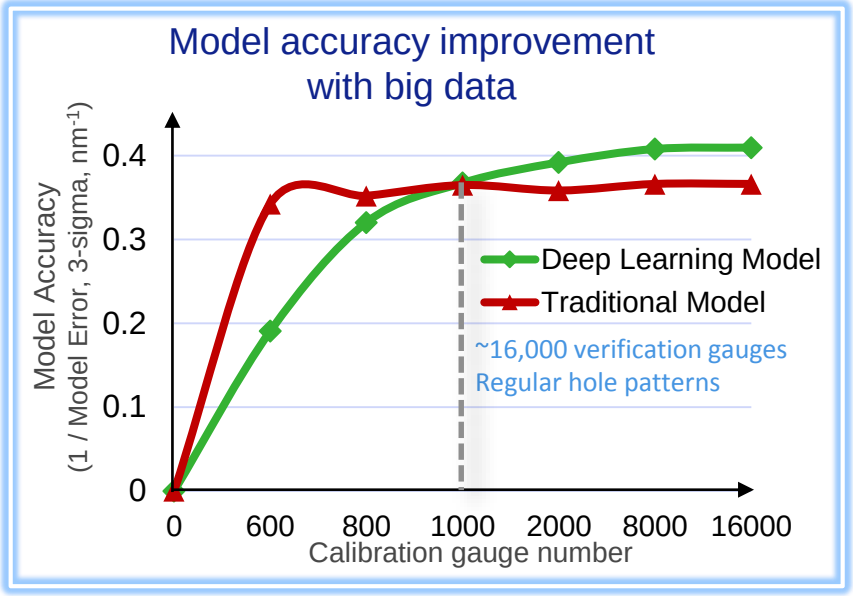
Model Accuracy: Percentage of gauges within spec



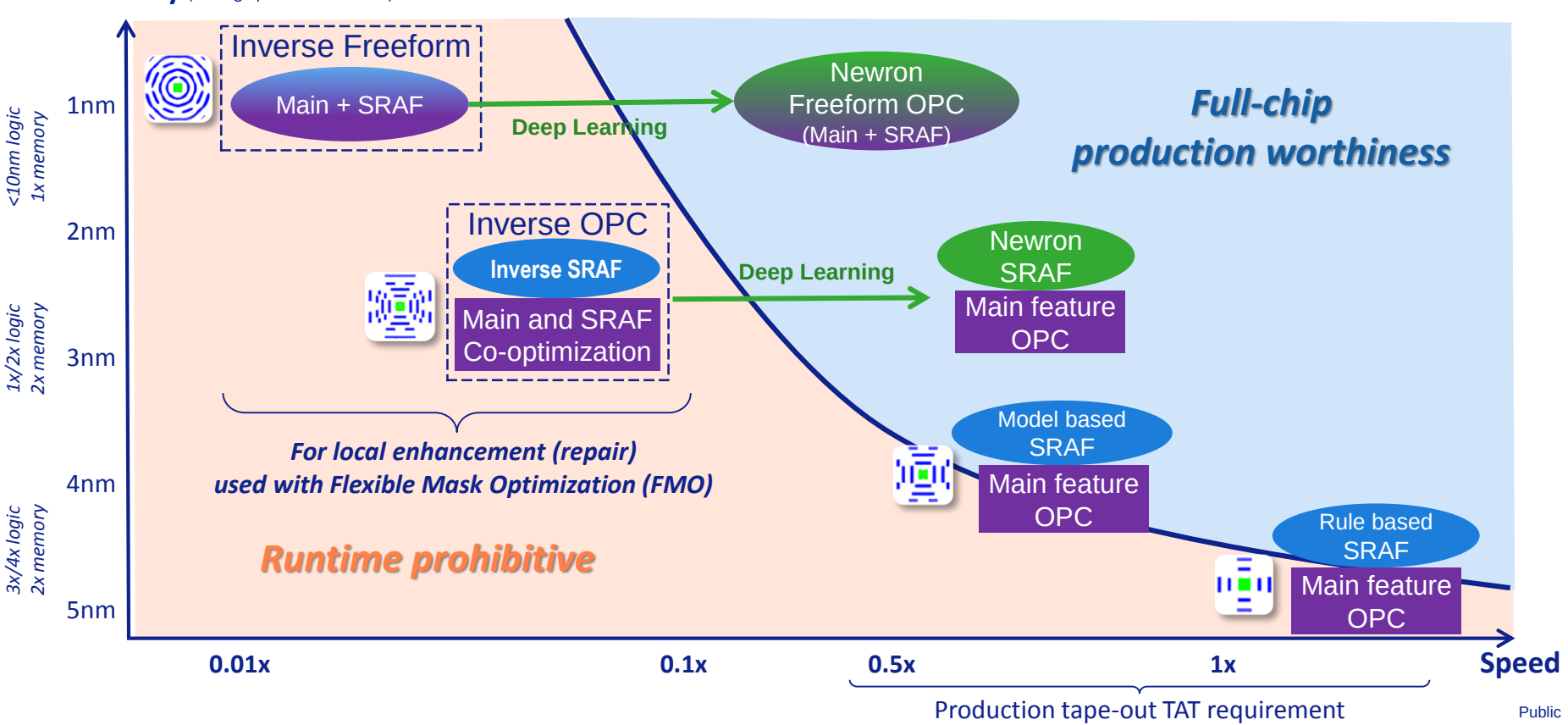
Massive metrology data & deep learning models further improve OPC accuracy in customer case

- Big data improve pattern coverage & enhance model accuracy
- Deep Learning Model has more benefits with big data vs Traditional Model





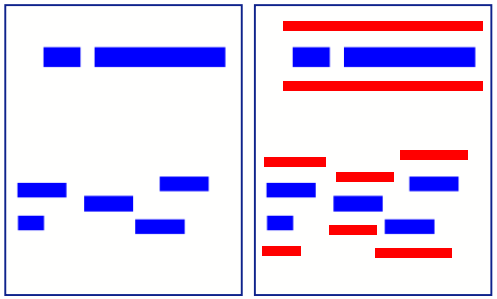
Deep learning enables full-chip application of inverse SRAF and OPC



Current SRAF placement methods

Targeting different development cost and use scenarios

Rule-based



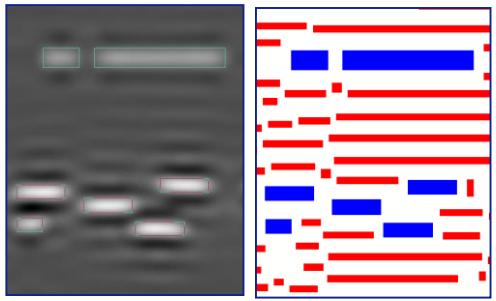
Development

- Time consuming and labor intensive work with trial and error.
- Very fast computation time. Complex 2D layout is a challenge.

Use case

Full chip application, best for simple or 1D pattern.

Model-based (SGM)



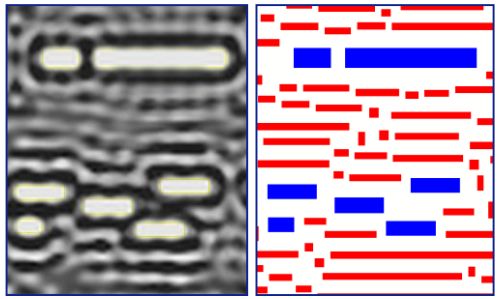
Development

- **SRAF Guidance Map (SGM)** uses gradient-based map calculation method.
- Efficient computation time.

Use case

Full chip application when rule is not good enough.

Model-based (CTM)



Development

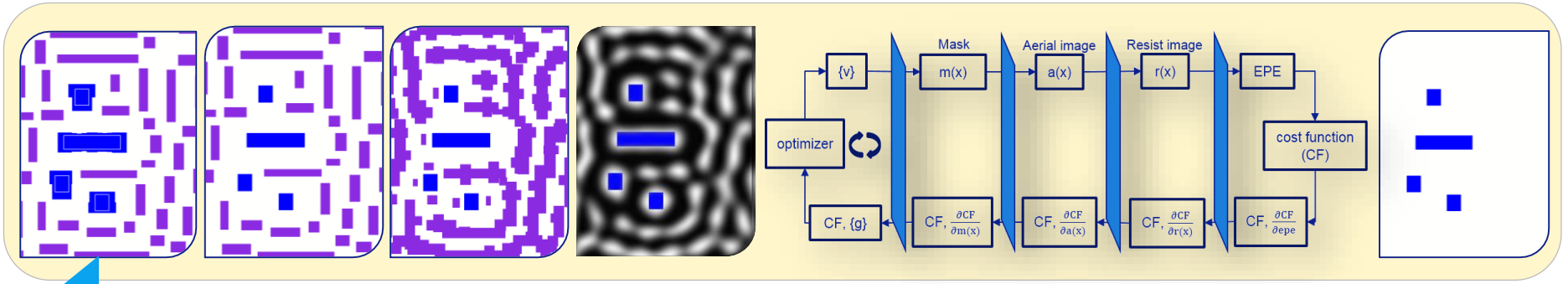
- Many iterations to optimize **Continuous Transmission Mask (CTM)** for SRAF extraction.
- Long computation time.

Use case

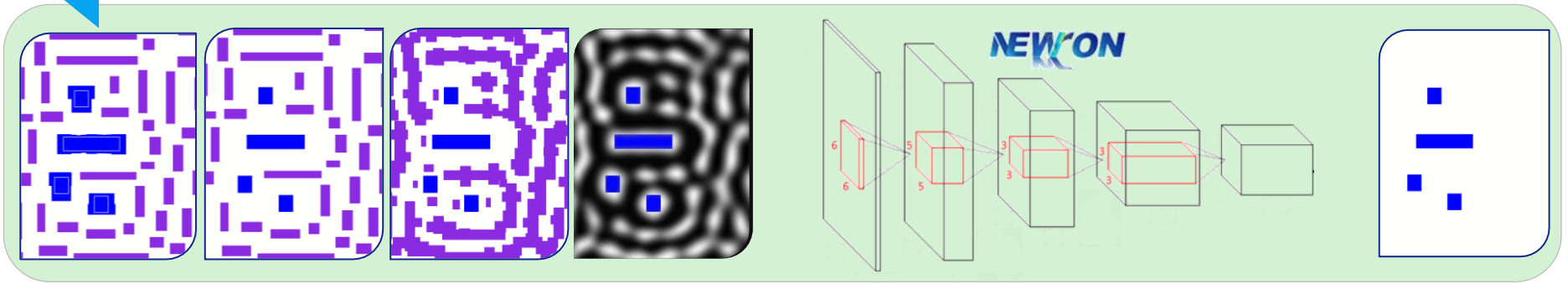
Clip based or local repair, key engine for Brion's inverse lithography solution (Tachyon SMO and iOPC).

DCNN for SRAF placement

Speed up the most accurate SRAF placement method (CTM)

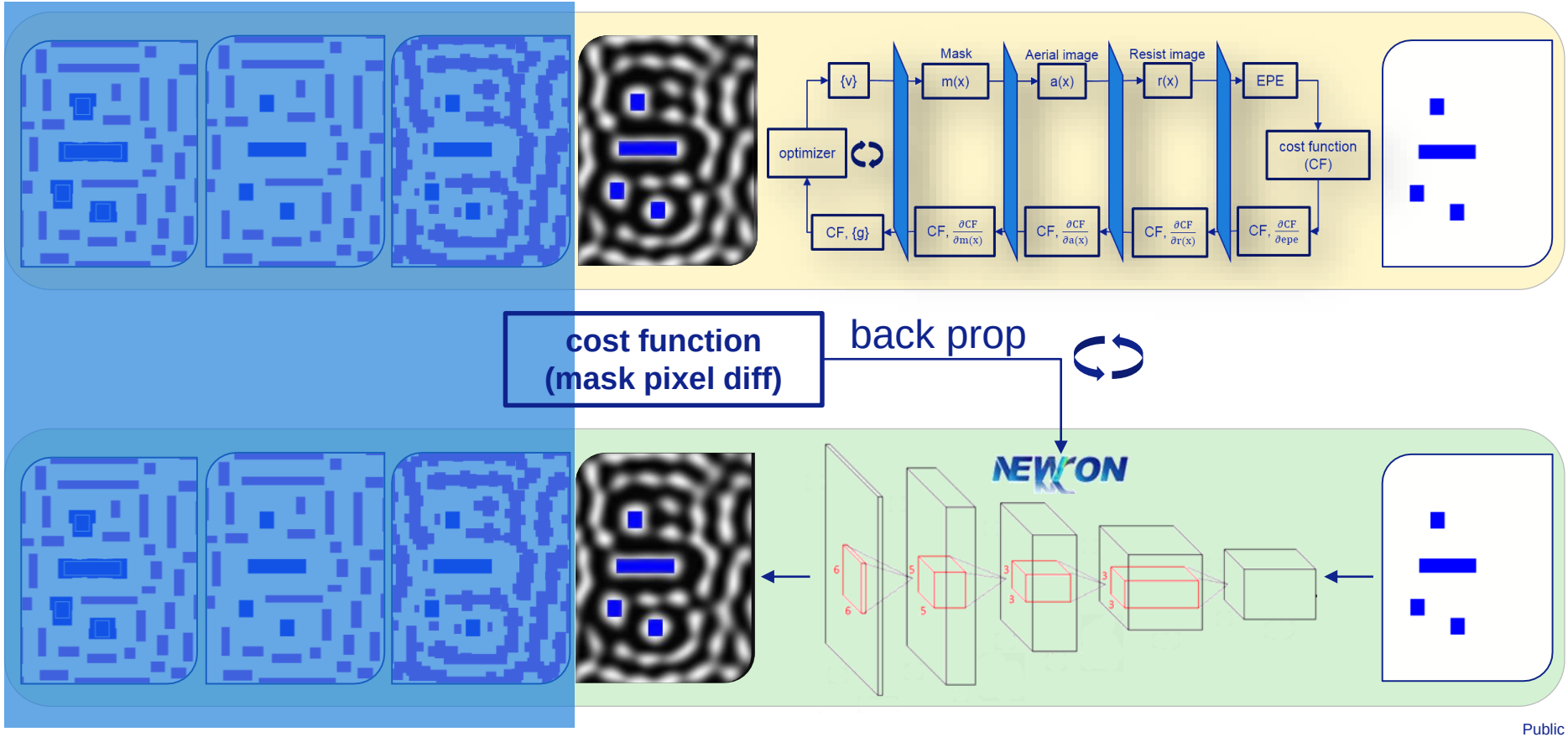


OPC | SRAF Clean-up | SRAF Extraction | Mask Image | Image-Based Mask Optimization | Target

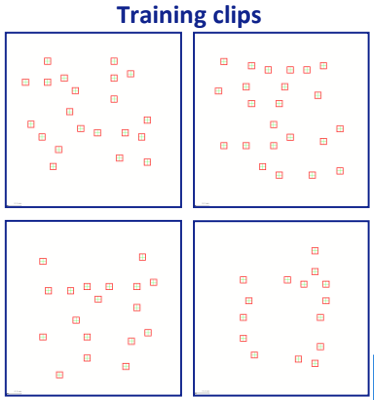


DCNN for SRAF placement: supervised learning

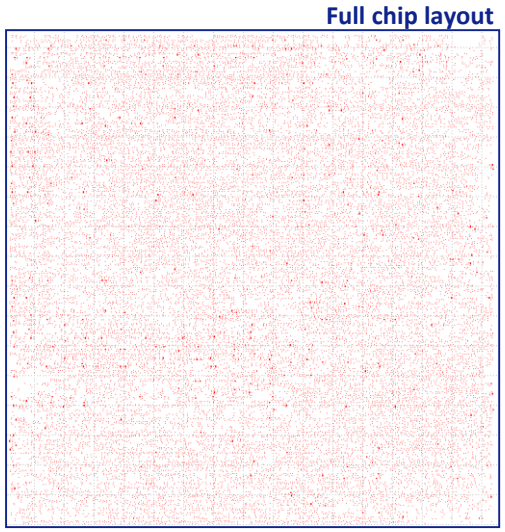
DCNN is trained using sample target and mask images



Training a Machine Learning SRAF model



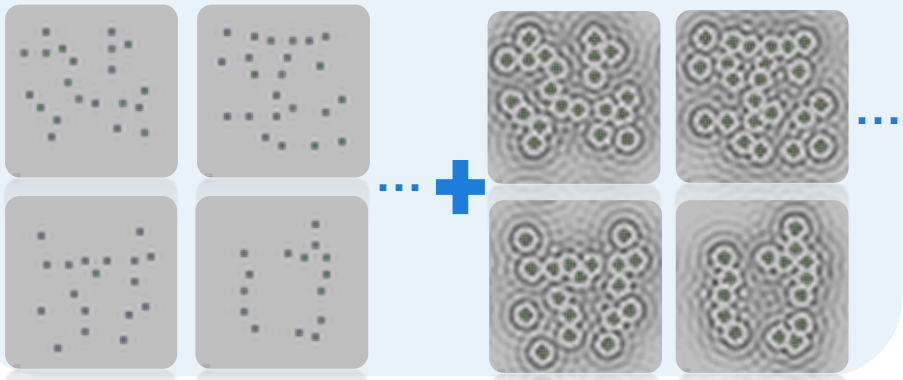
Training Pattern Selection



Wafer target images

CTM mask images

Training input



ML training

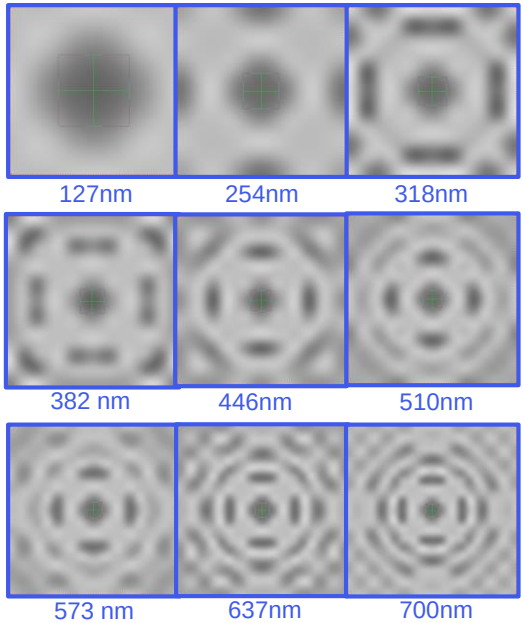
NEWRON SRAF model

Deep convolutional neural network

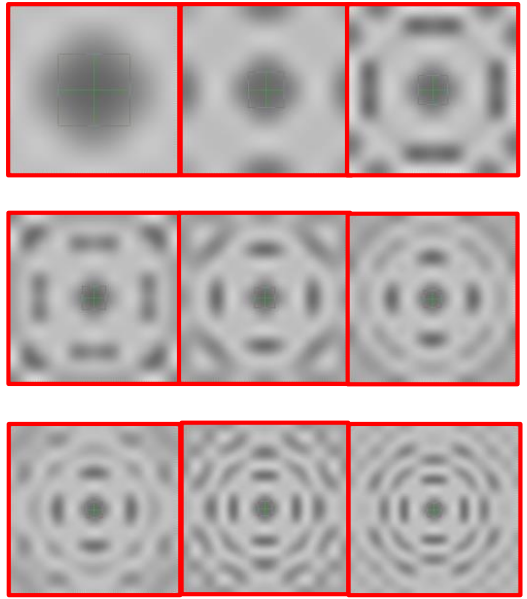
Deep learning assisted SRAF litho performance

- Contact holes through pitch (CD: 54nm, Pitch: 127nm to 700nm)

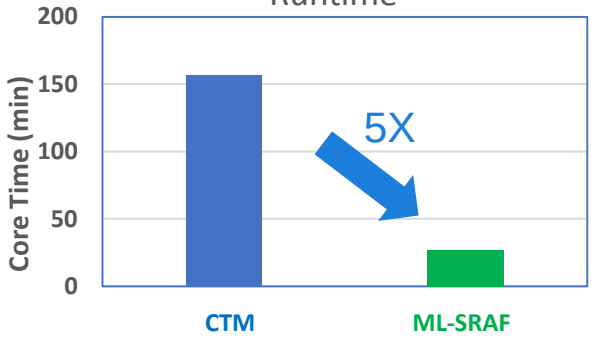
Ground truth CTM



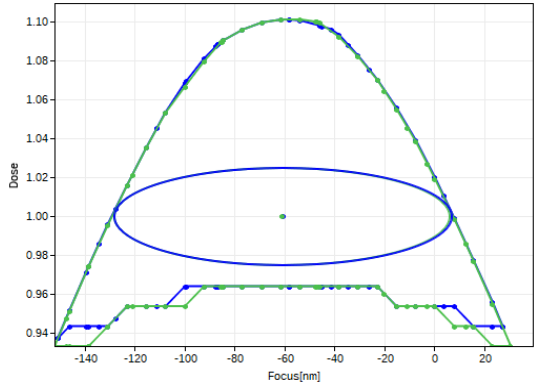
Direct predict - SRAF



Runtime



Overlap PW Comparison

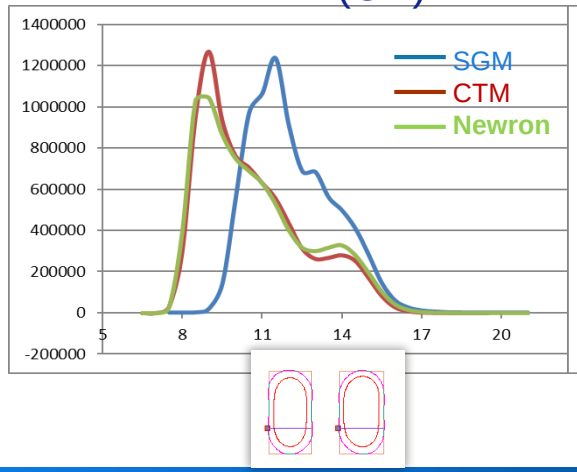


Comparison of PV band distribution

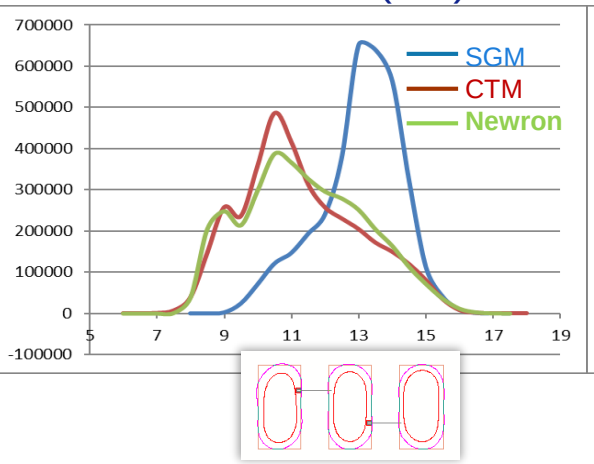
Nominal Condition (NC) OPC with different SRAF generations

- Design: Advanced node contact layer, 6.5 mm^2
- Lithography model: ArFi FlexRay, bright field
- SRAF by SGM/CTM/Newron + nominal condition OPC
- Maximal PV band from wide PW conditions

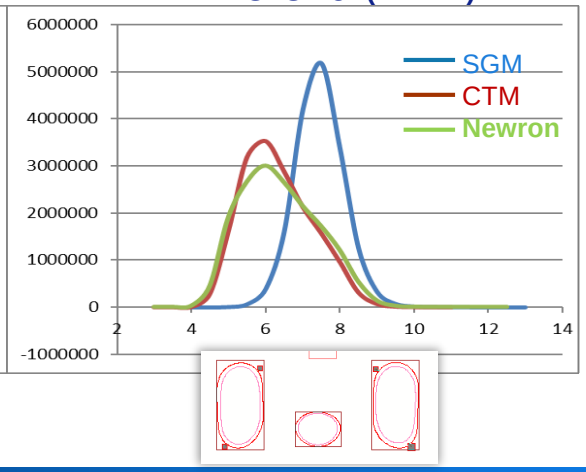
1D (CD)



1D slot (CD)



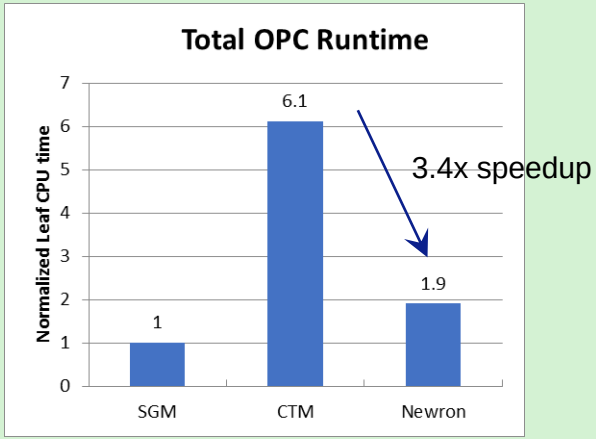
Line-end (EPE)

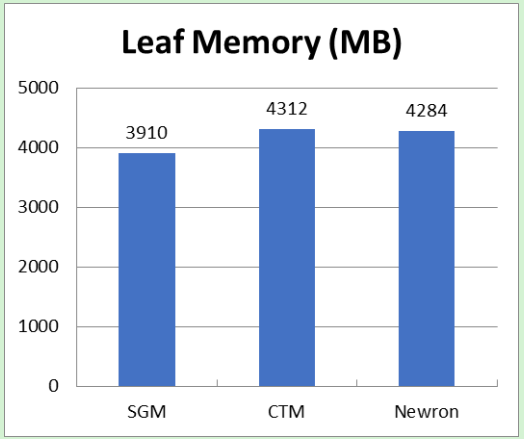


Statistically, Newron SRAF PV band is smaller than SGM
Newron SRAF follows what it learned from CTM

Runtime and memory

Full Chip OPC job with SRAF generation and Process Window OPC



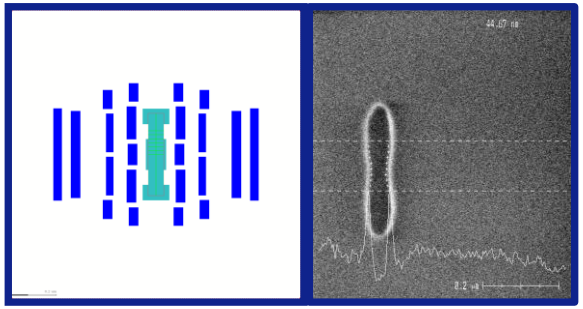


Newron SRAF OPC job is 3.4x faster than CTM in runtime and uses only 9% more memory than baseline SGM.

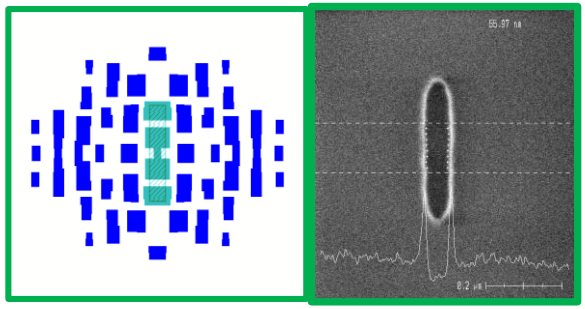
Wafer validation of Freeform OPC+ on 3D-NAND via layer

32% improvement in DOF

MO

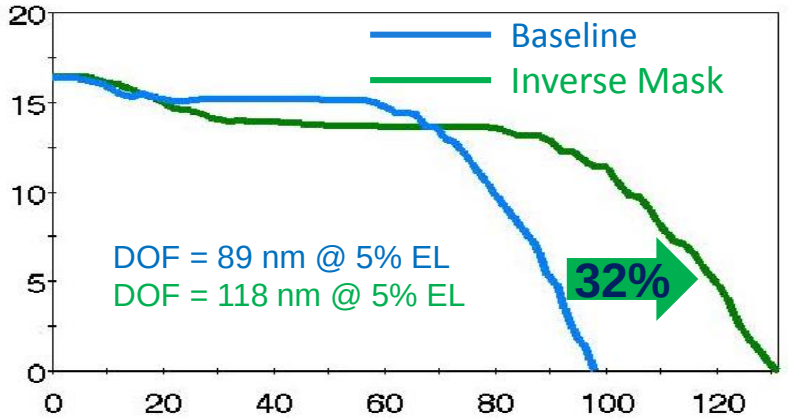


Freeform OPC



Necking observed with MO is not seen with Freeform OPC

	Simulation DOF @ 5% EL	Wafer DOF @5% EL
Freeform OPC	136nm	118nm
	↑ 32%	↑ 32%
Baseline (MO)	103nm	89nm



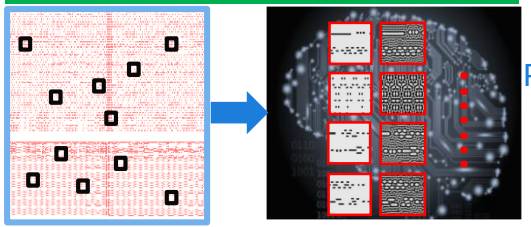
[SPIE 2018] Sam Liu, " Freeform mask optimization using advanced image based M3D inverse lithography and 3D-NAND full chip OPC application"

Freeform OPC+ delivers accuracy of inverse OPC to full chip

Conventional OPC with MB-SRAF
Insuffiecient accuracy but meets runtime requirements

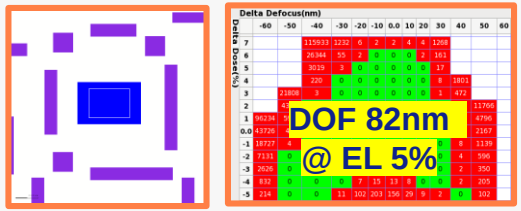
Freeform OPC+
Best accuracy but too slow for full chip

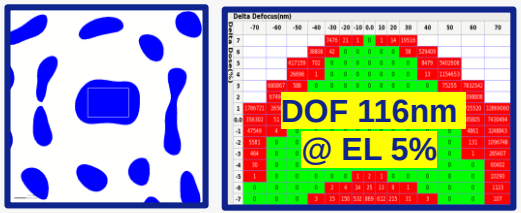
Newron Freeform OPC+
Trained with Inverse on selected patterns



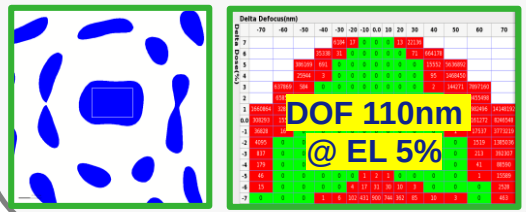
ML Prediction

DUV Test case

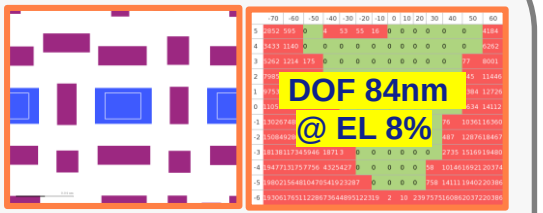


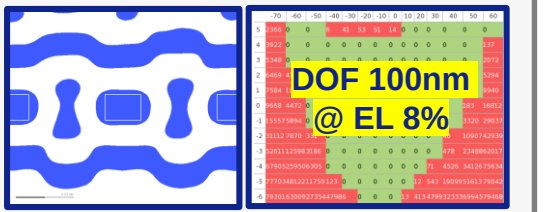


Significant speed-up!

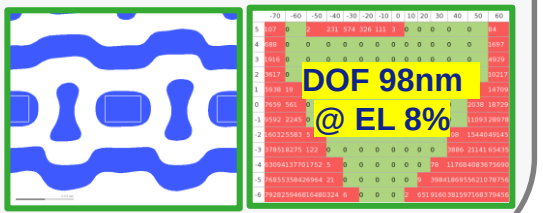


EUV Test case

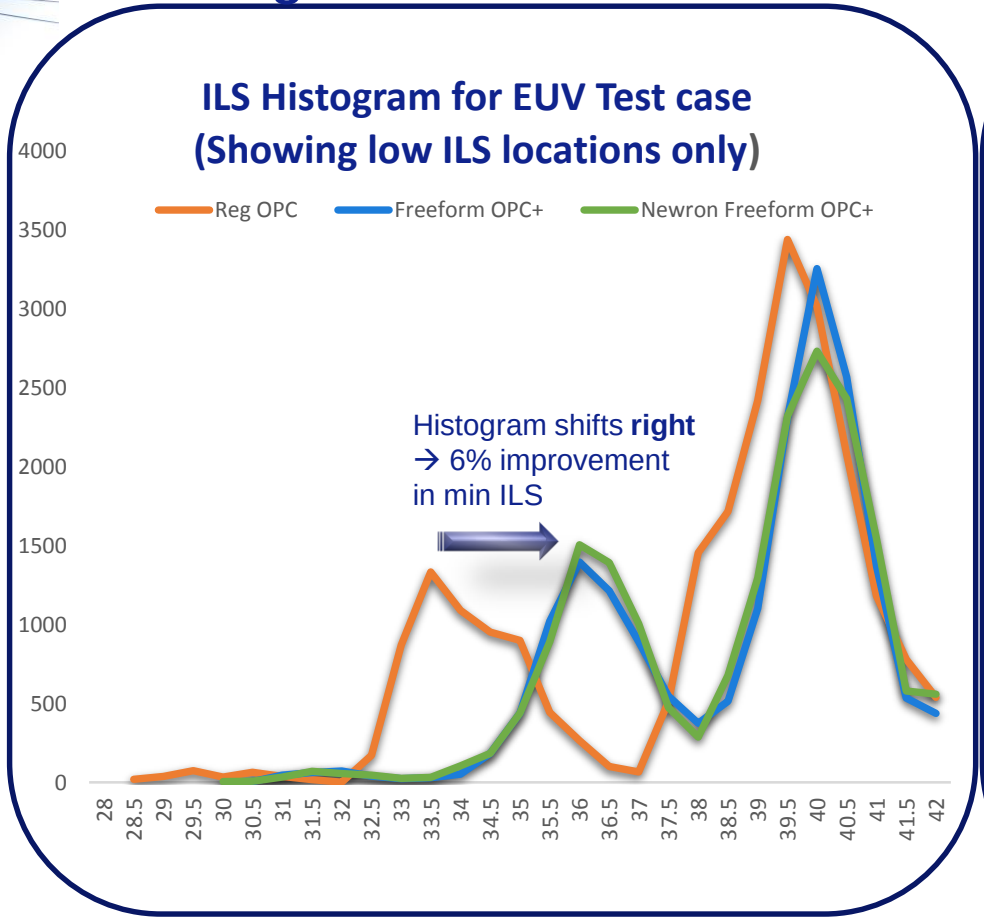


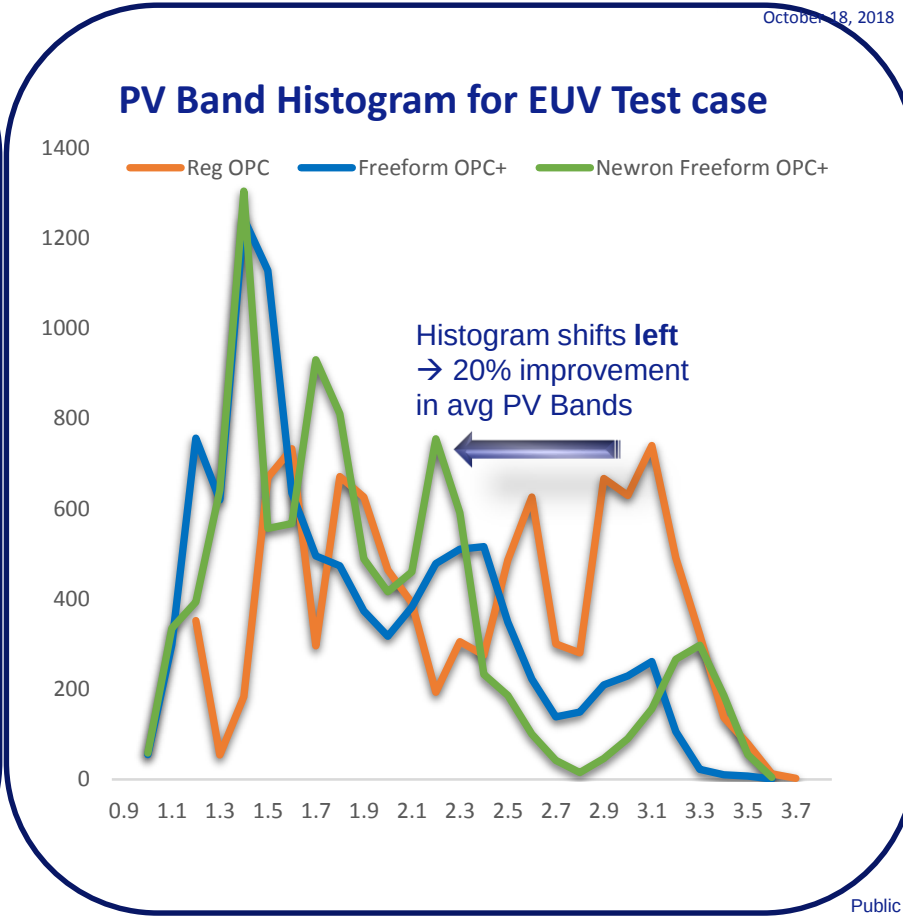


Significant speed-up!



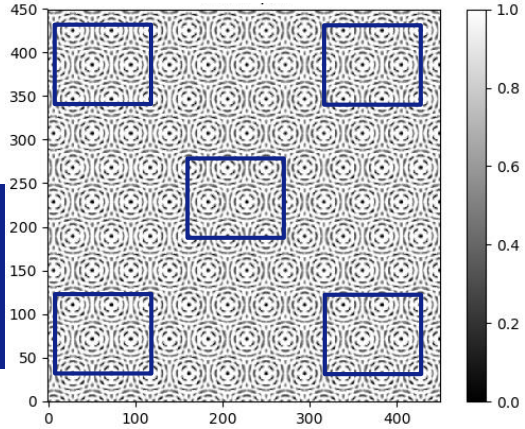
Newron Freeform OPC+ improves ILS and PV Bands, reducing total EPE

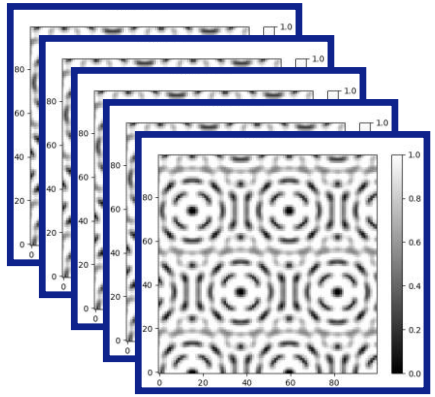


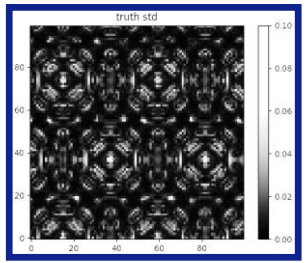


Newron Freeform OPC+ improves image consistency

Freeform OPC Ground Truth

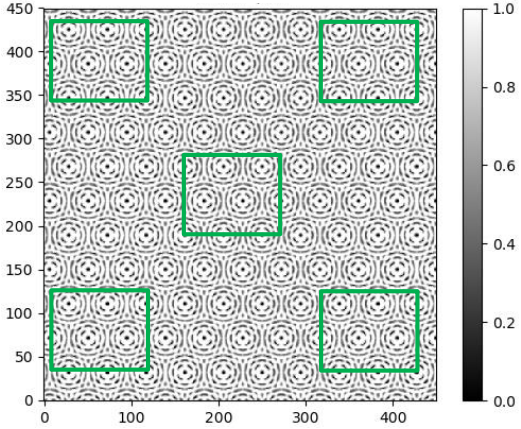


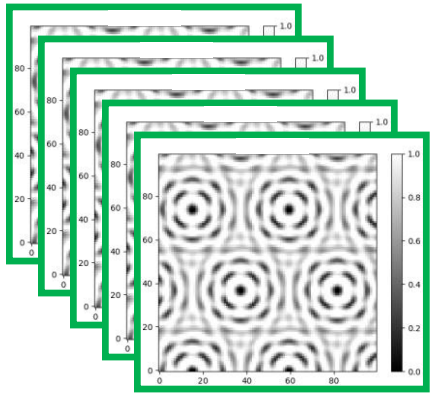


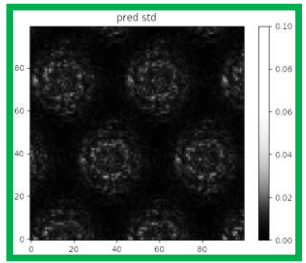


Std = 0.0120

Freeform OPC Deep Learning



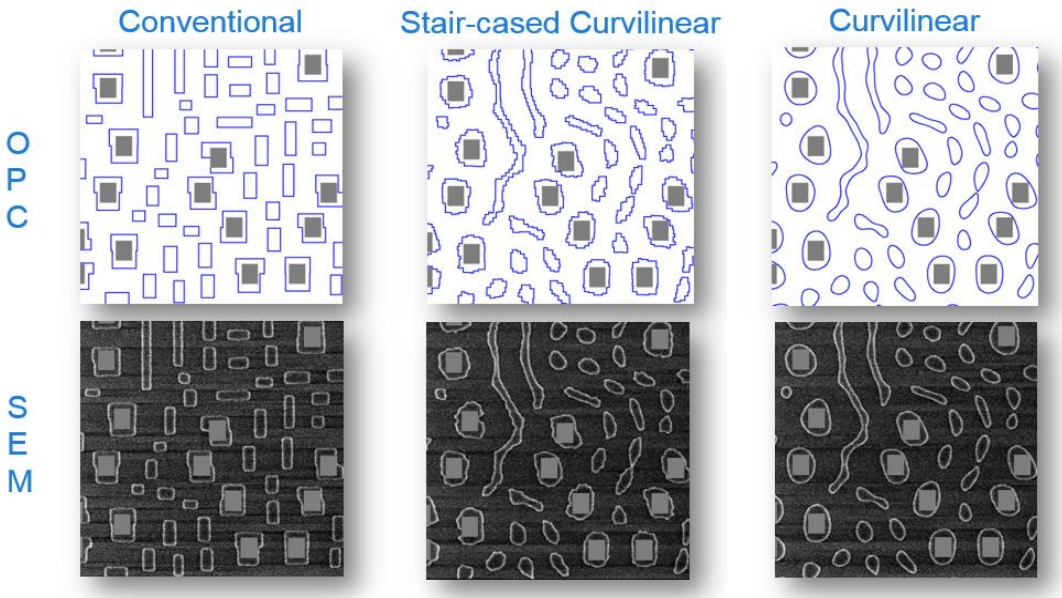




Std = 0.0065

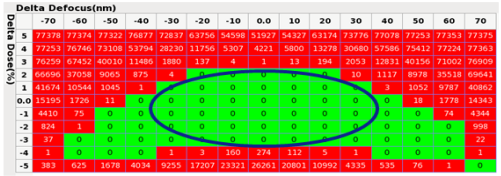
46% improvement in consistency

Curvilinear masks can be made using VSB or MBMW

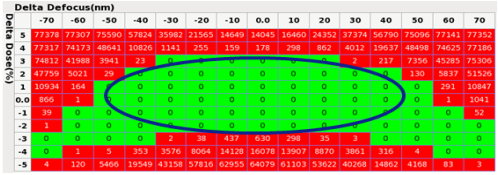


Process window comparison

Conventional mask: DOF=96 nm @ 5% EL



Curvilinear mask: DOF=112 nm @ 5% EL



Mask type (DUV)	VSB with conventional fracturing In Hours per Full Field	VSB with freeform fracturing In Hours per Full Field	MBMW In Hours per Full Field
Conventional mask	**12.6**	-	**12.4** (30 v/um^2)
Stair-cased curvilinear mask	**95.0**	-	**12.4** (169 v/um^2)
Curvilinear mask	**757**	**79**	**12.4** (164 v/um^2)

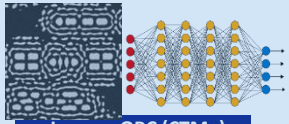
Spence et al., "Manufacturing challenges for curvilinear masks", Proc. SPIE 10451, Photomask Technology, 1045104

Leverage confluence of new technologies to meet OPC technology and cost requirements

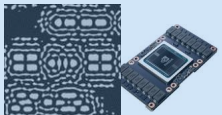
2016	2017	2018	2019	2020	2021

ASML

Inverse OPC (CTM)



Inverse OPC (CTM+) Deep Learning Inverse



Inverse with phase control Hardware Accel. (tentative)

intel

Intel DL Boost

14 → 10 nm

NVIDIA

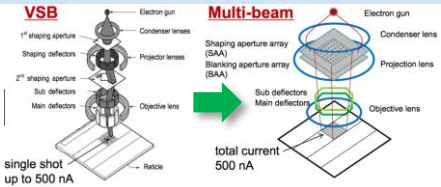
Pascal

Volta

Turing

Next Gen?

Mask writer & inspection



Multi-beam Mask Writer available

Mask inspection available

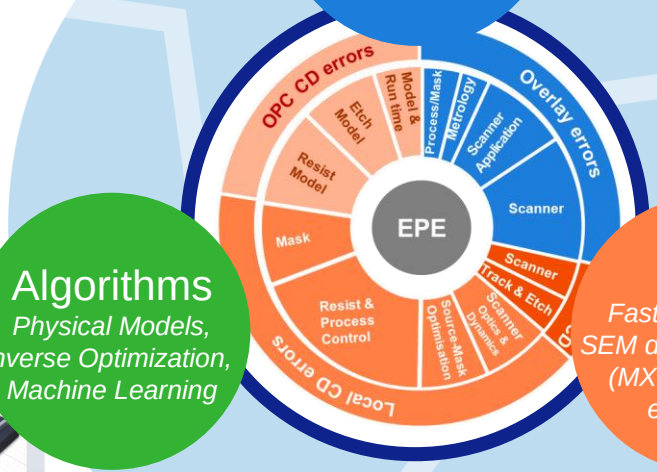
Mask making infrastructure is ready for inverse OPC & curvi-linear masks

Data, algorithms, and applications for patterning solutions

Lithography scanner with advanced control capability

Etch and deposition tools

Applications
Mask, Litho, & Etch Pattern Fidelity Control



Algorithms
Physical Models, Inverse Optimization, Machine Learning

Data
Fast SEM (eP5), SEM data processing (MXP), other fab equipment

Computational lithography and metrology

Optical and e-beam metrology

ASML