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Optimization of mask error correction quality for low-k1 curvilinear mask lithography

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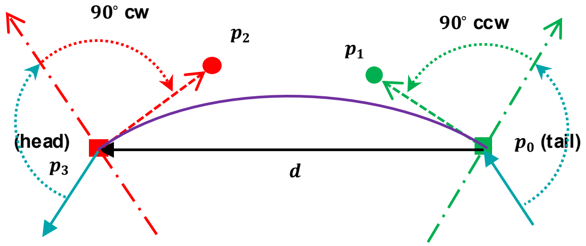
Outline

- Introduction to curvilinear mask lithography flow
- Curvilinear Mask process data and modeling
- Curvilinear Mask error correction (MEC) and verification
- Curvilinear Mask correction file size implications
- Summary

Full curvilinear mask ecosystem requirements

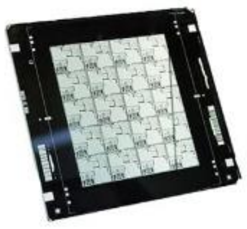
- Users need a full flow of curve/Multigon-ready solutions to quickly and accurately complete steps from Process Dev to Mask write



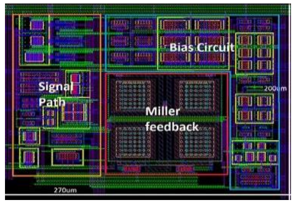
Full MEC Curvilinear Flow Support

Test Pattern Definition → Data Collection & Analysis → Model Calibration, Verification → Mask Rule Check → MEC & Verification → Mask Data Fracture

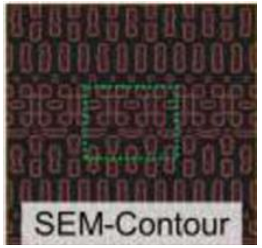
Need: Curve Data Representation, Simulation and Synthesis

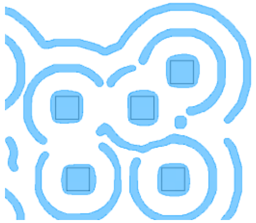


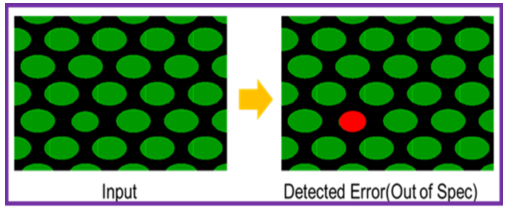
Mask

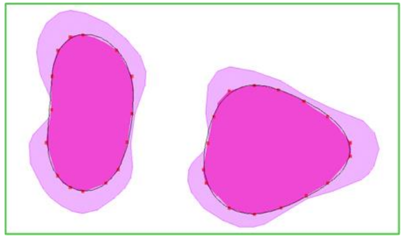


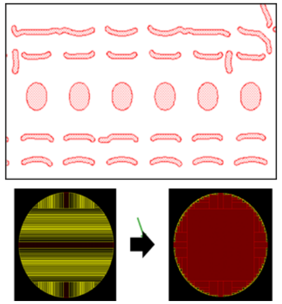
Design



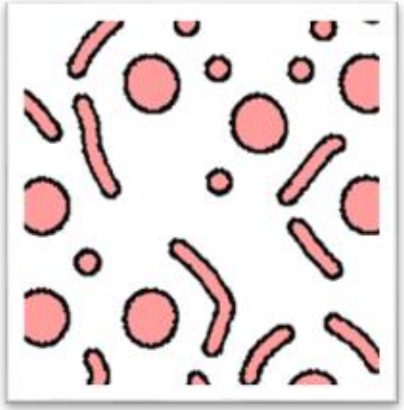


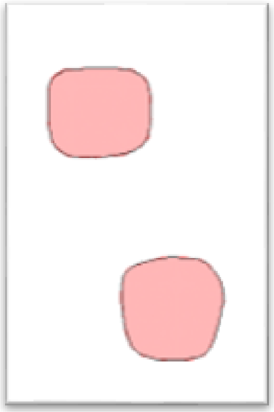




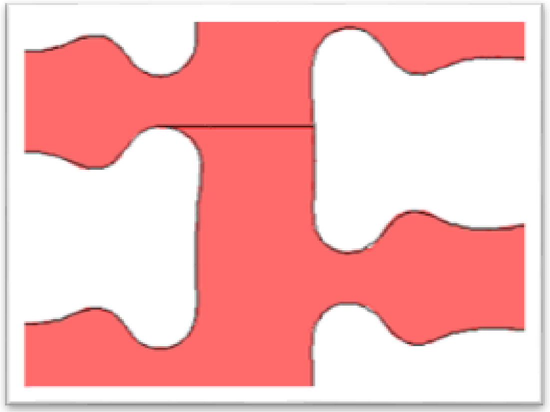


Experimental setup used in this work





- Manhattan and curvy test patterns used for MEC model calibration and validation
  - CD linearity, through-pitch, small to large areas, main and assist features, 2D complex shapes



- 3 different curvilinear layout types (w/ OPC not optimized for MEC)
  - Circular, semi-circular and rectangular main feature (MF) vias
  - Dense main features with curvy inside/outside corners
  - Main curvy features with small space-end to space-end
  - Small CD/area (high-curvature) circular and quasi-circular AFs
  - Long AFs w/bends and line-ends
  - Small jogs & bevels. Sharp and round corners with curvature > mask process resolution

- Varied 2D pattern arrays E-beam written on mask for validating full flow MEC accuracy

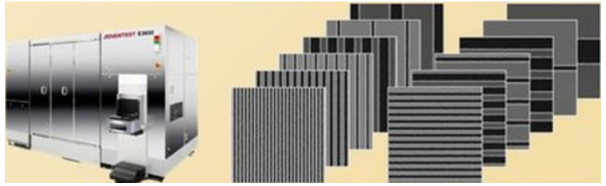
Curve mask proximity data and modeling

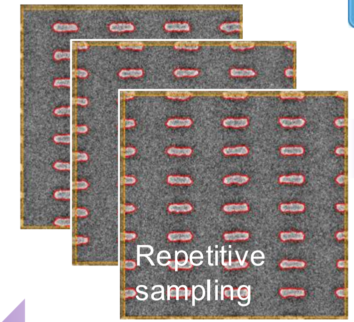
Mask model calibration flow with ML option

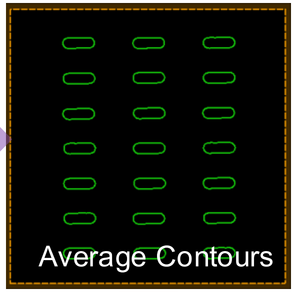
Layout & data Input

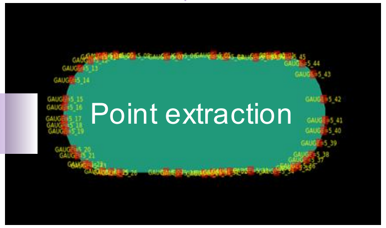
Model components

Modeling Process









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2	1_02	point	1	2	228.5982...	TILE_CH2...
3	1_03	point	1	3	236.1648...	TILE_CH2...
4	1_04	point	1	4	240.1546...	TILE_CH2...
5	1_05	point	1	5	241.9003...	TILE_CH2...
6	1_06	point	1	6	245.9687...	TILE_CH2...
7	1_07	point	1	7	285.9116...	TILE_CH2...
8	1_08	point	1	8	303.5467...	TILE_CH2...
9	2_01	point	2	1	239.6946...	TILE_CH2...
10	2_02	point	2	2	241.6917...	TILE_CH2...
11	2_03	point	2	3	246.001444	TILE_CH2...

Point input format

Reviewed input Measurements
~2-10k patterns

Reviewed input Contours
Many 100k's of points

Layout Info. Optical Flare + Long Range Effect (LRE) Map

CD measurement Ave, Clean & Down-sampling ~1k patterns

Contours Ave & Down-sampling ~Few 100k's of points

Process Information:
NTD/PTD resist tone, mask filmstack, multi-dose exposure…

Compact modeling:
Compact E-beam image, resist PEB/DEV, etch biases, long-range

(Optional) ML modeling:
Image training + EpE optimization

Model validation:
1D and 2D, CD and Ep points, long-range effects

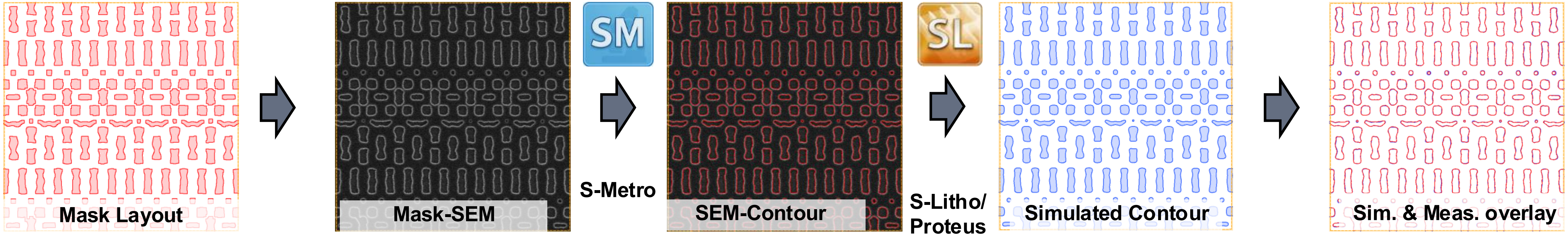
Model output

C-I. Wei et al. Machine Learning Enhanced Optical Proximity Correction Modeling for High-NA EUV Lithography. Proc. SPIE Vol. 13980, 2026
J. Bekaert et al. High-NA EUV mask CD-SEM metrology matching, and contour-based comparison of simulation result and wafer print. Proc. SPIE Vol. 13687, 2025

Curve mask patterns, data extraction & model calibration results

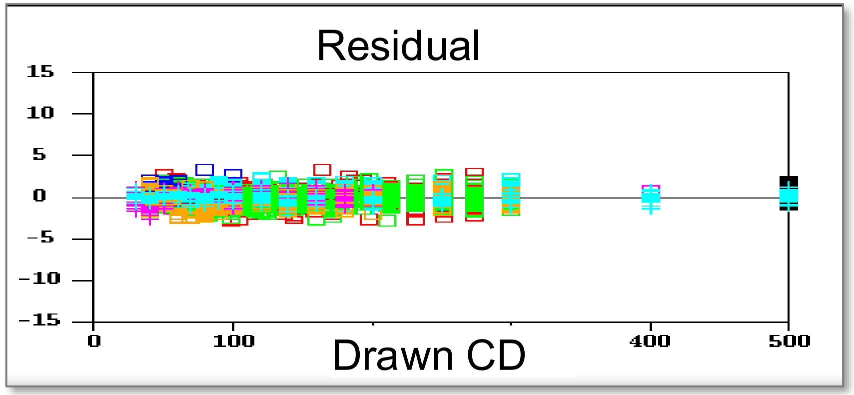
SEM extraction flow for model calibration & validation

M. Ramadan et al.
Proc. SPIE Vol. 13216-29, 2024

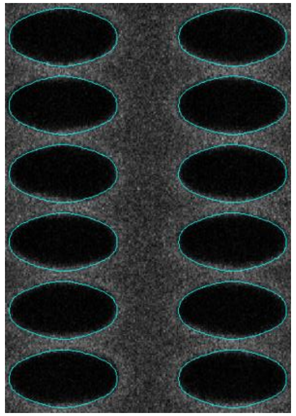


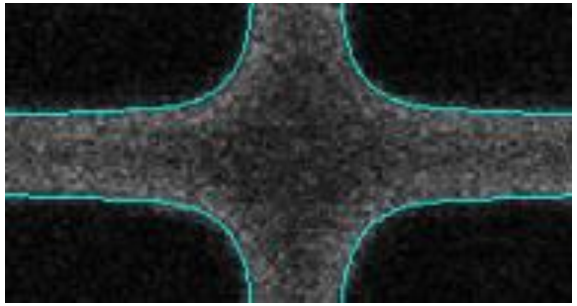
Model calibration results

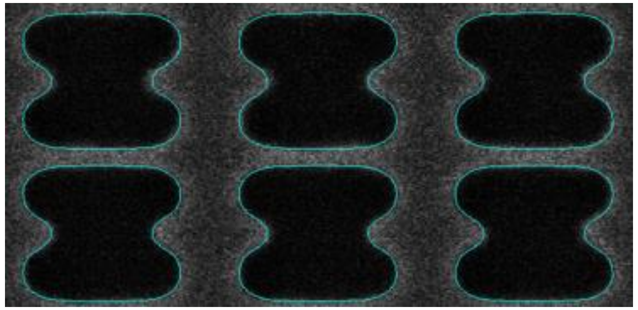
Gauge Type	# Gauges	RMS
CD	4397	0.8nm
Edge point (EP)	147,777	1.0nm

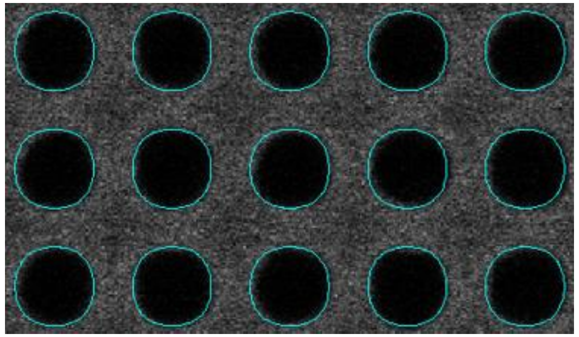


SEM/contour overlay results







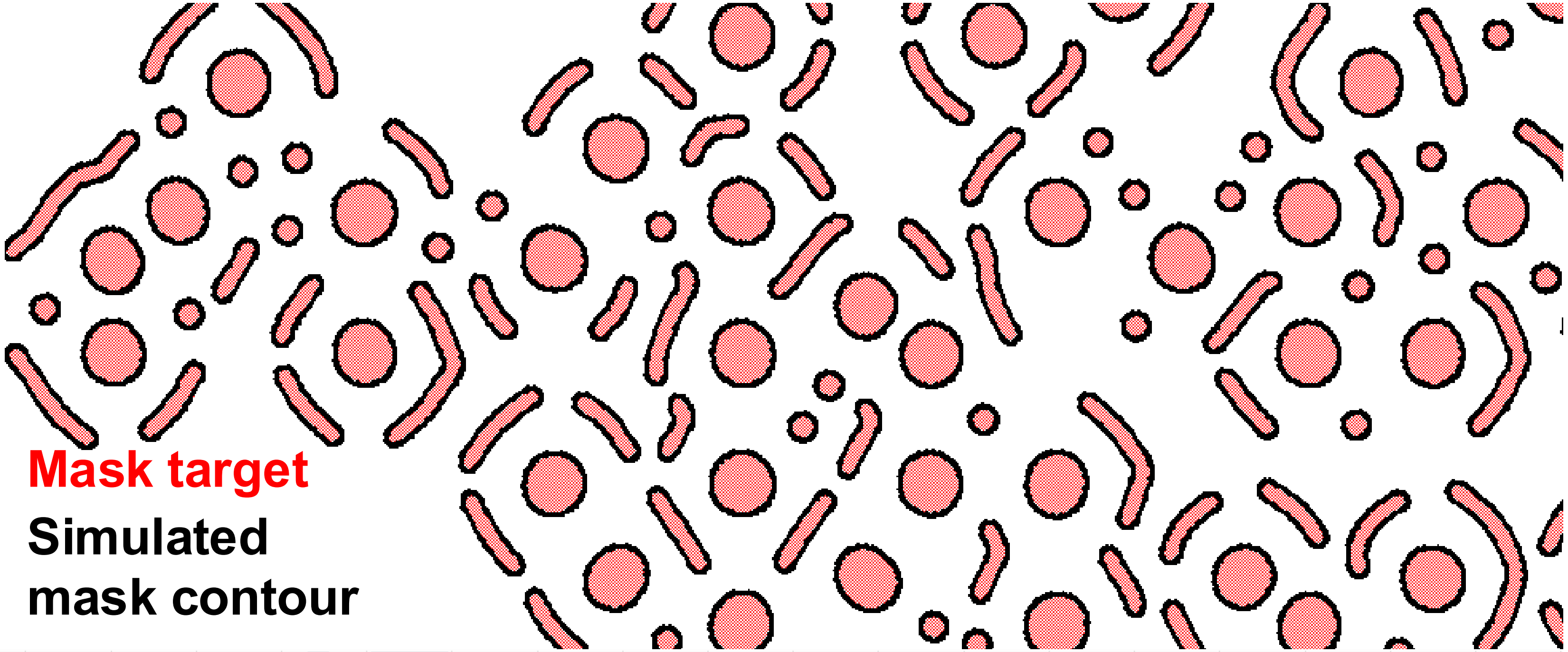


Target mask pattern vs. simulated MEC results

Curve layout1 – simulated contours vs target example

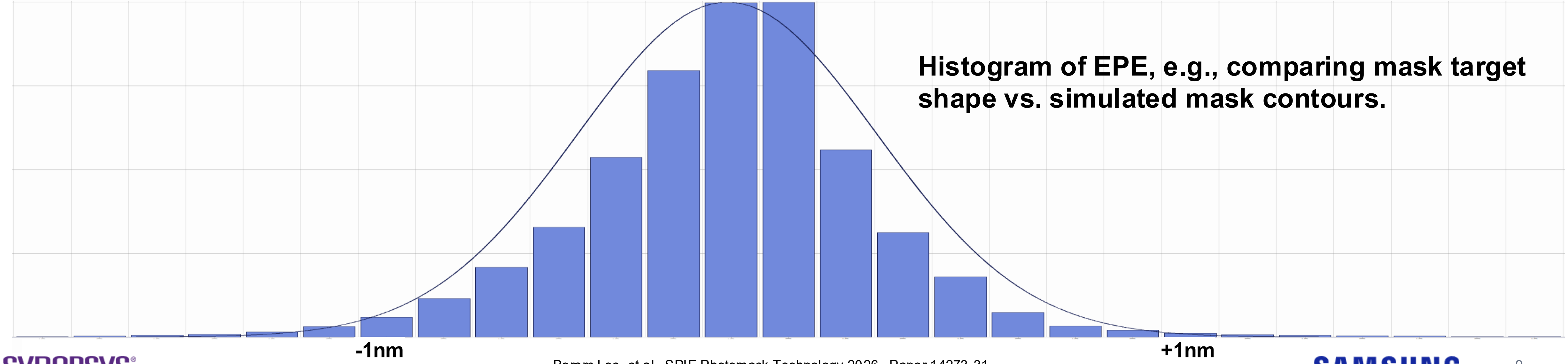
Simulated contours match the mask target well through many different pattern types:

- large vias
- small circular Afs
- long AFs w/bends
- long AF line-ends



Mask target

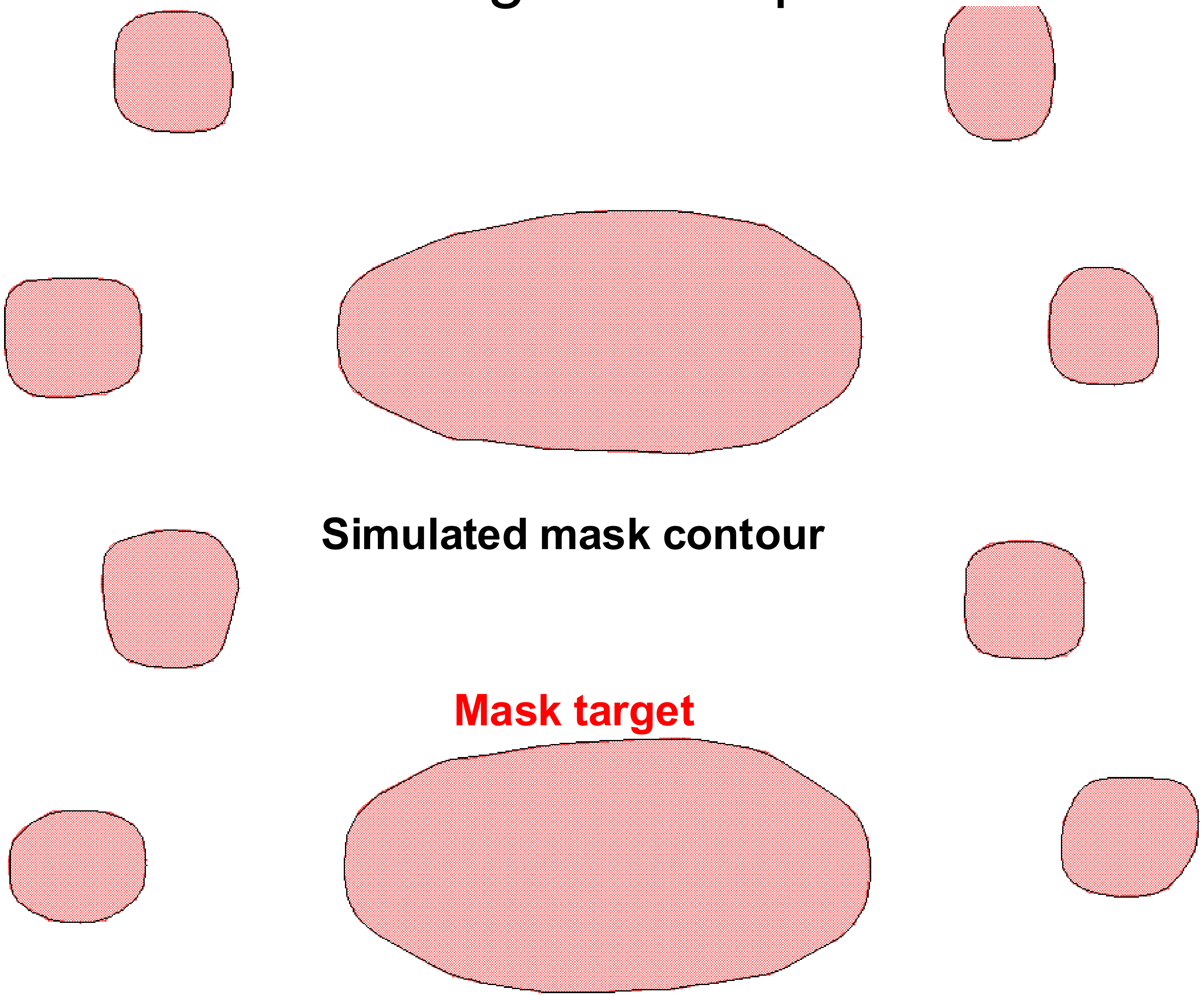
Simulated mask contour



Histogram of EPE, e.g., comparing mask target shape vs. simulated mask contours.

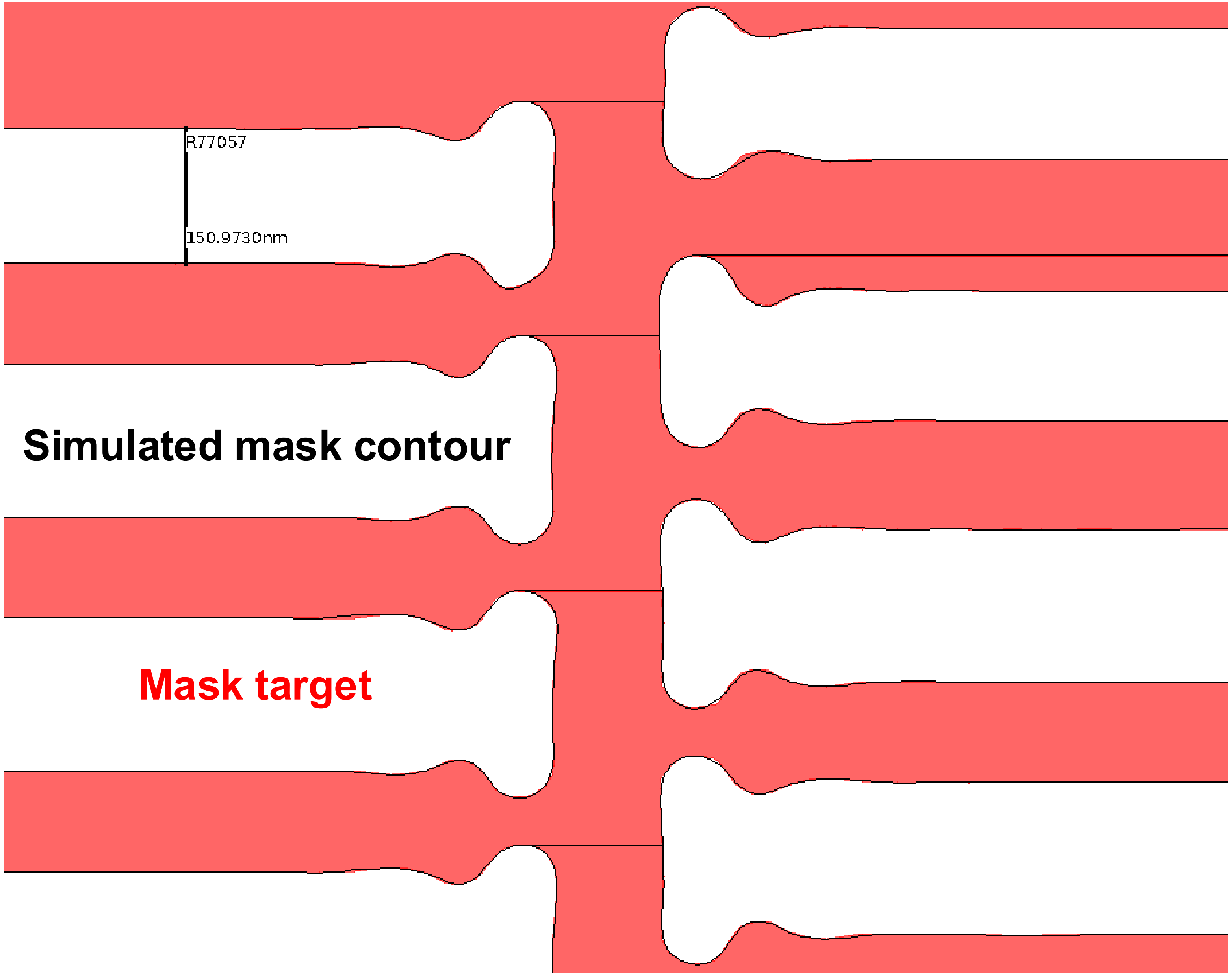
Curve layout2 – simulated contours vs target example

Simulated contours match the target mask well on additional pattern types:
- **large rectangular vias**
- **small quasi-circular AFs**

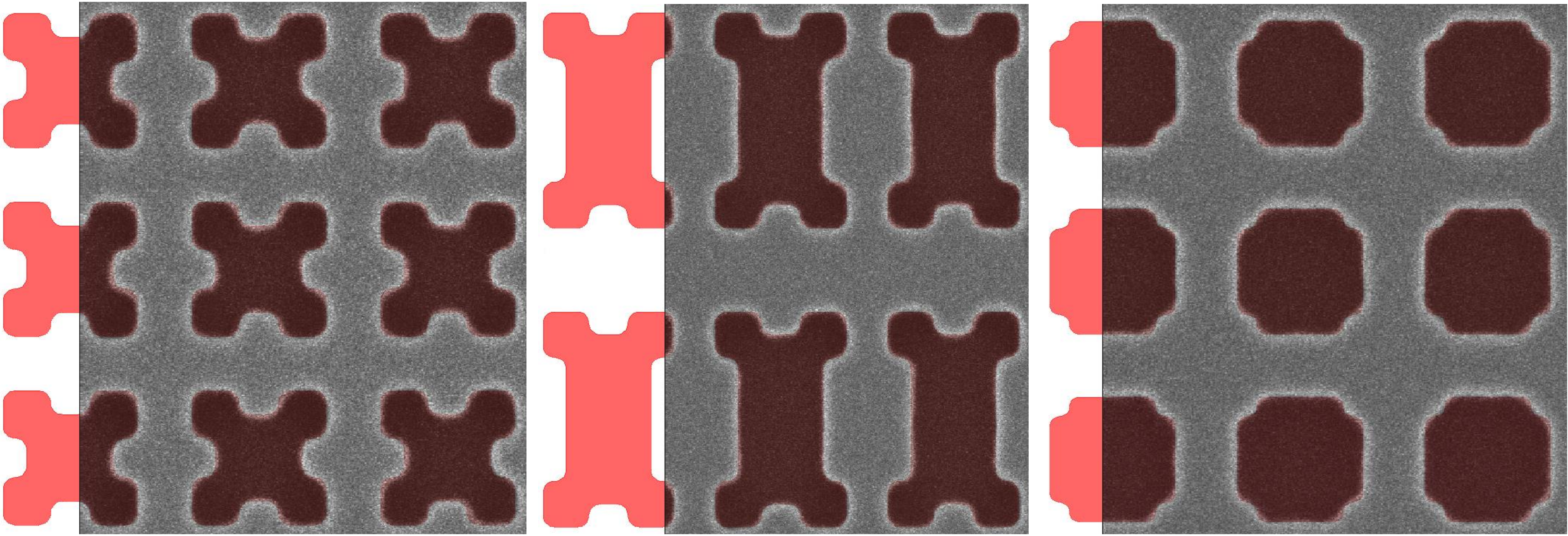


Curve layout3 – simulated contours vs target example

Simulated contours match the target mask well on additional pattern types:
- **dense MF w/round corners**
- **MF space-end to space-end**



Post-MEC mask SEM images show very good shape fidelity
- Mask written with MEC model & MEC correction described above

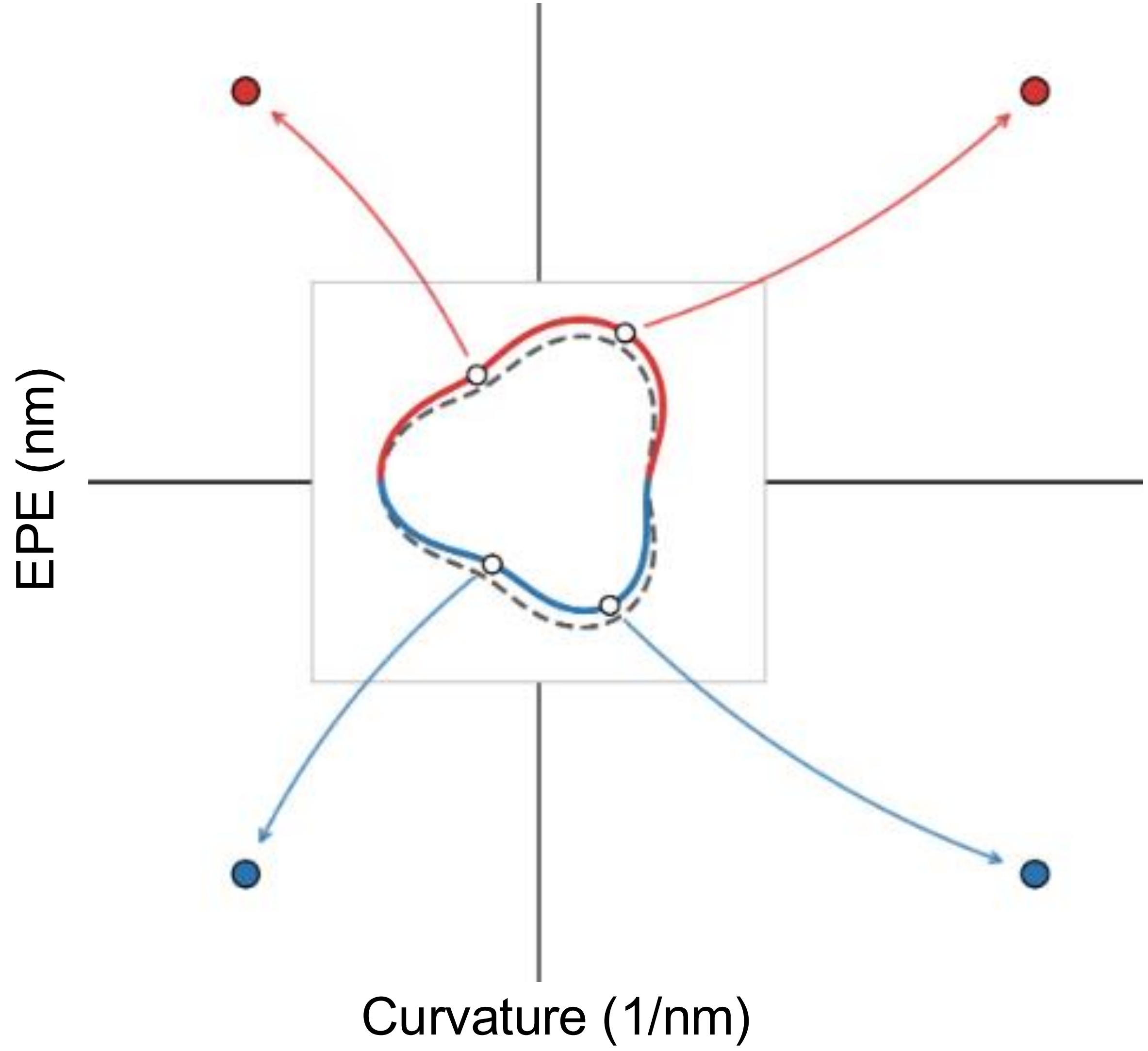


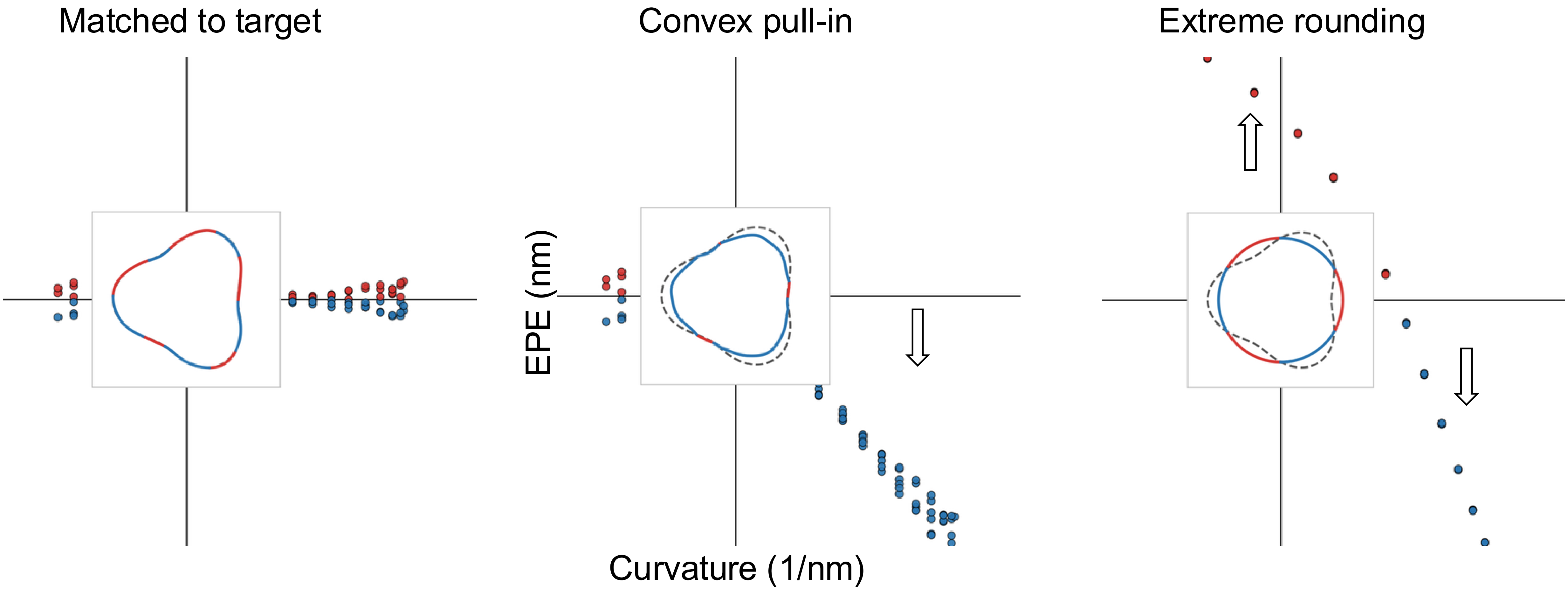
Patterns show improved curve and squared features resolution vs POR

Min width and space in features varies from ~30-60nm (4X)

S-Metro for MEC results visualization & analysis

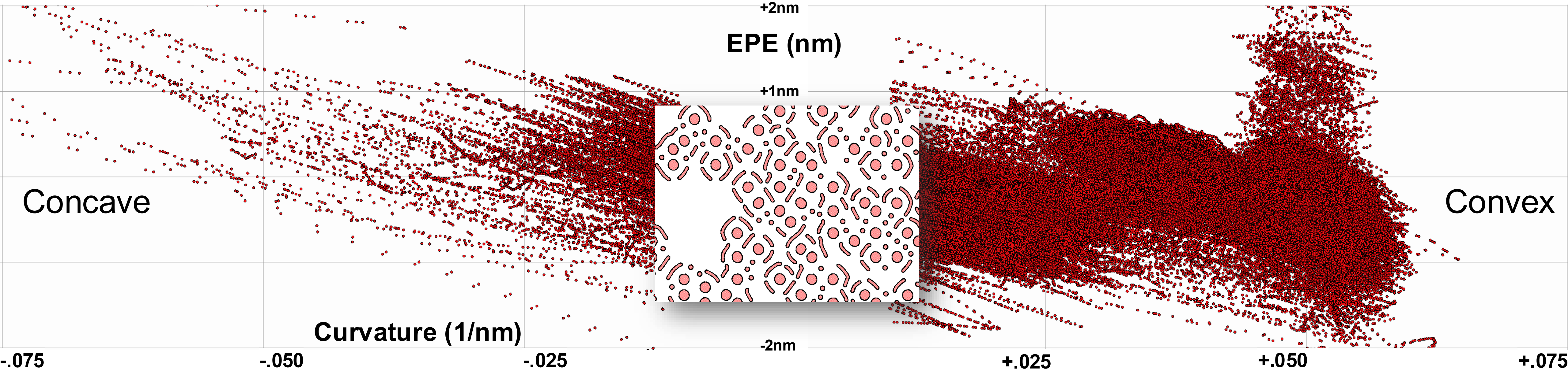
EPE vs Curvature visualization

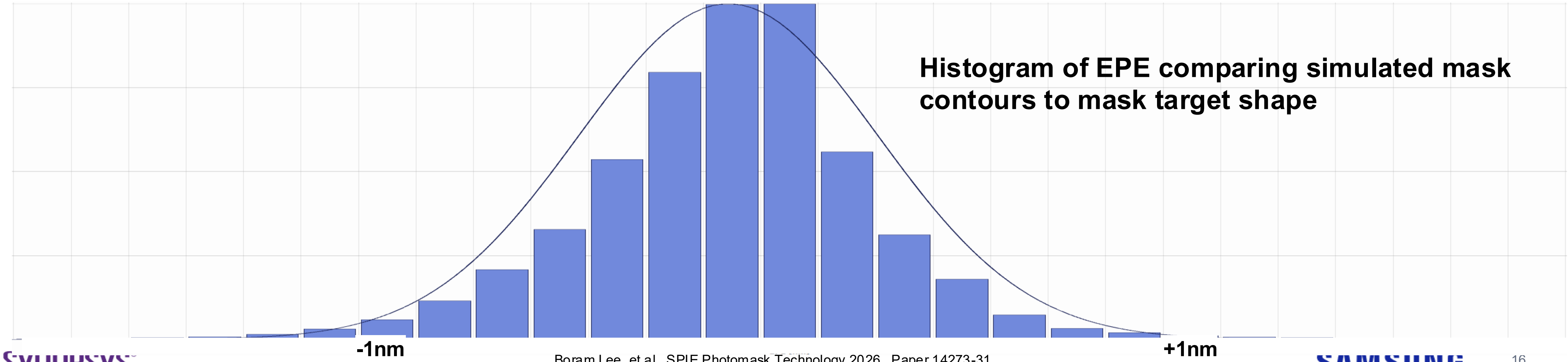



Matched to target
Convex pull-in
Extreme rounding
EPE (nm)
Curvature (1/nm)

Analysis methods for comparing contours to mask targets

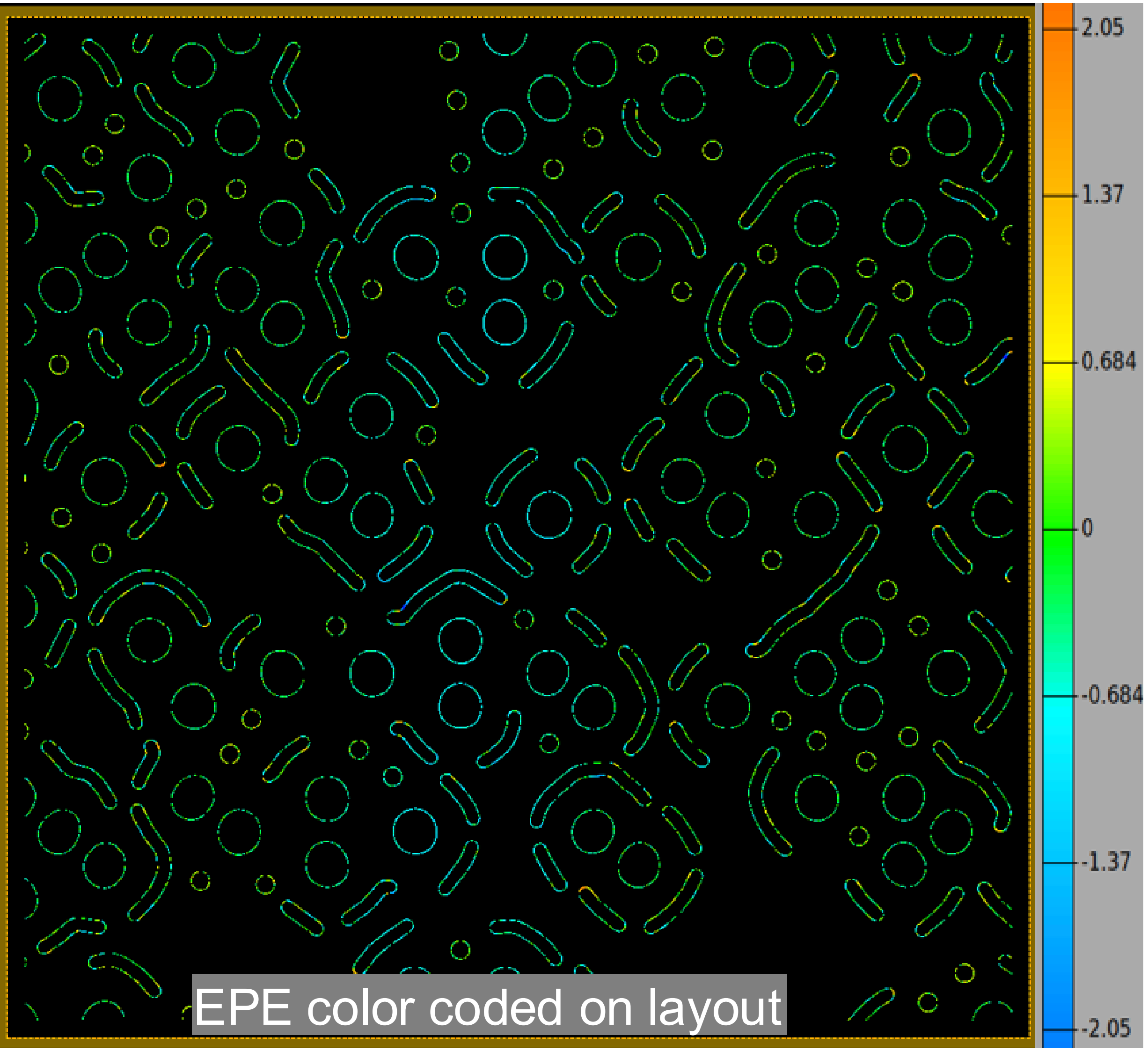
EPE vs Curvature plot comparing simulated mask contours to mask target shape

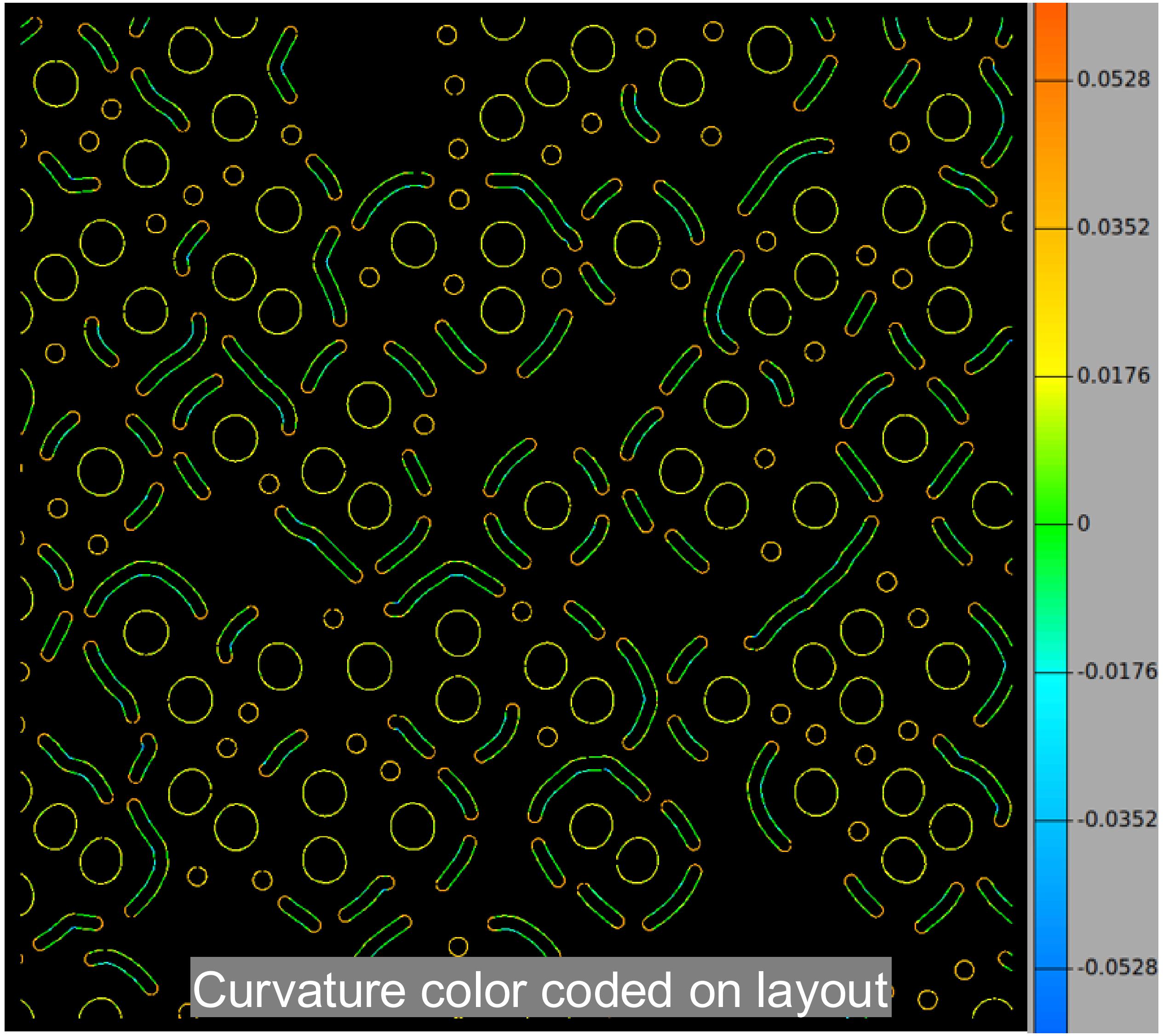




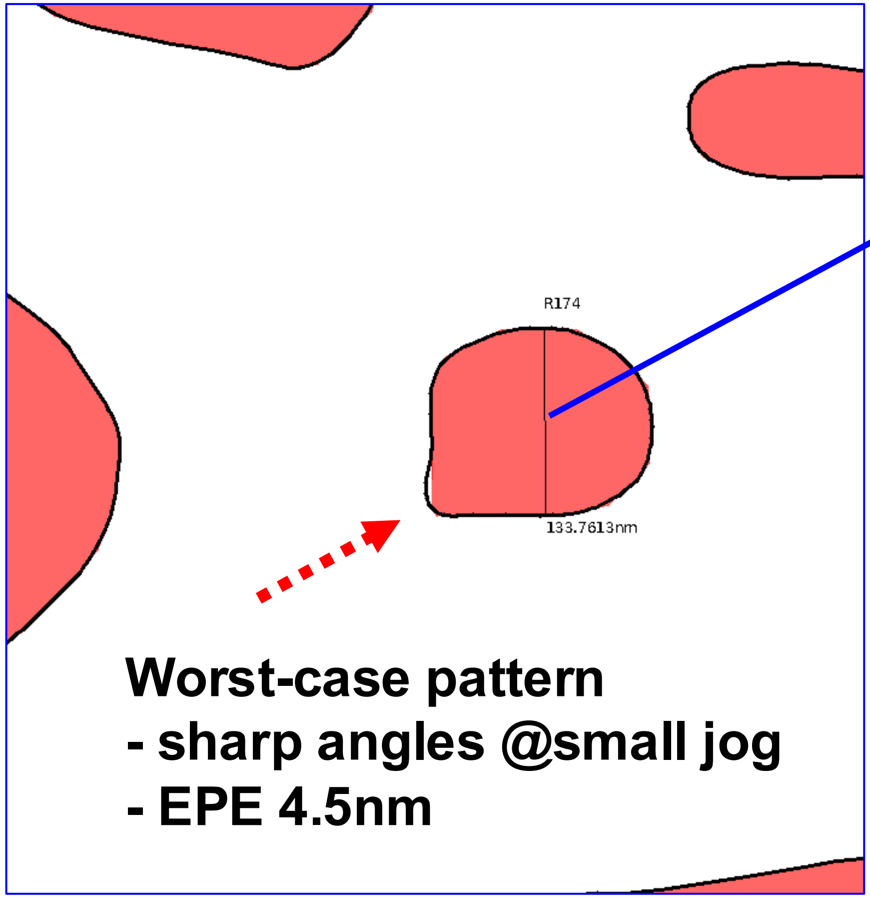
Histogram of EPE comparing simulated mask contours to mask target shape

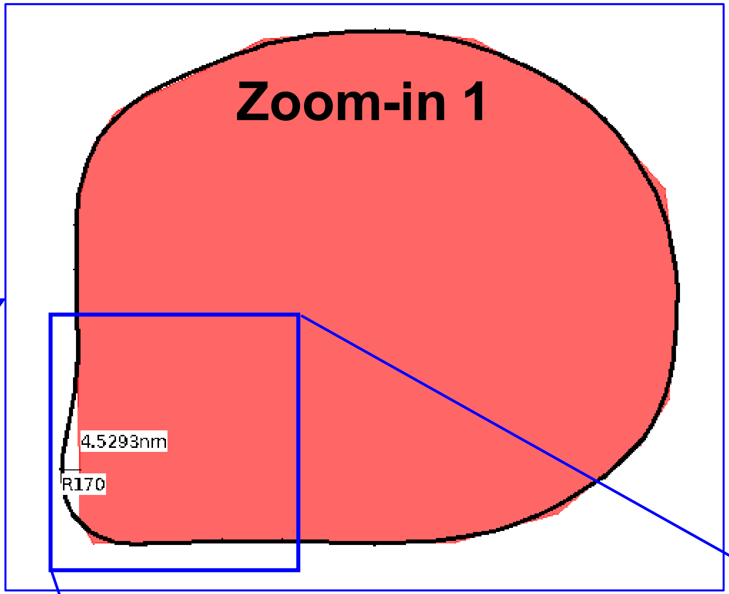
Further analysis methods for understanding MEC results
→ EPE & curvature contours to mask target

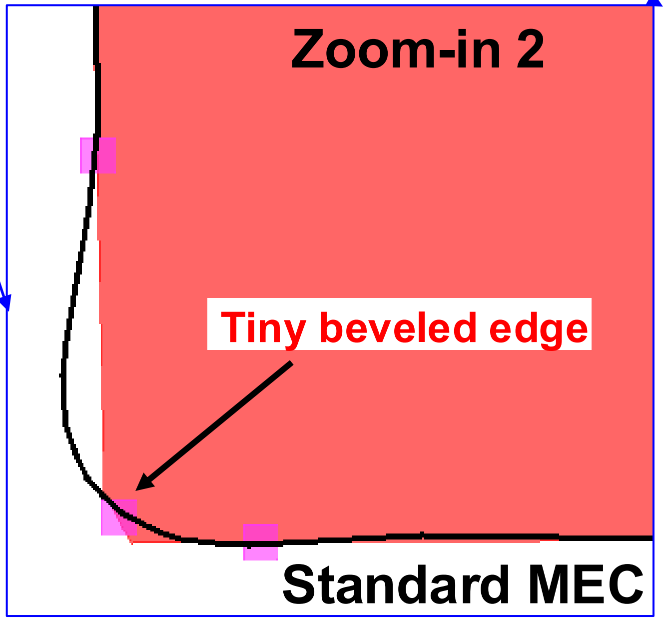


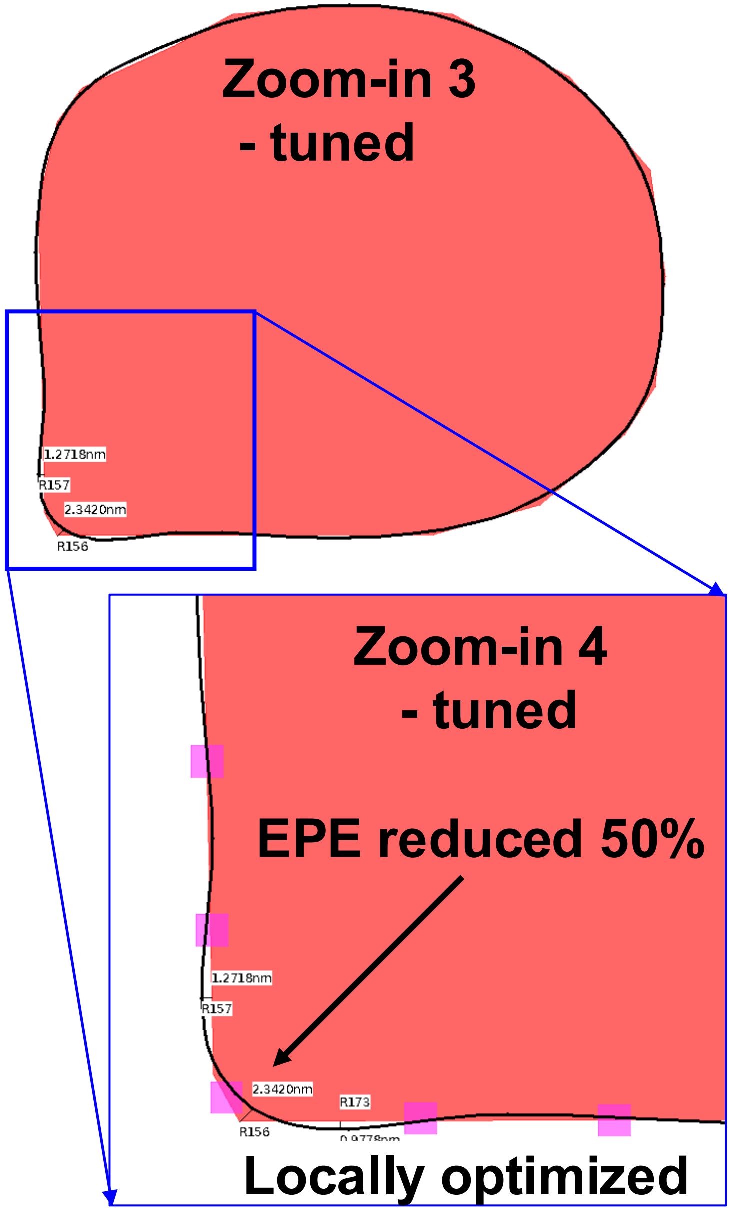


Tuning MEC for unfriendly post-OPC curvilinear shapes



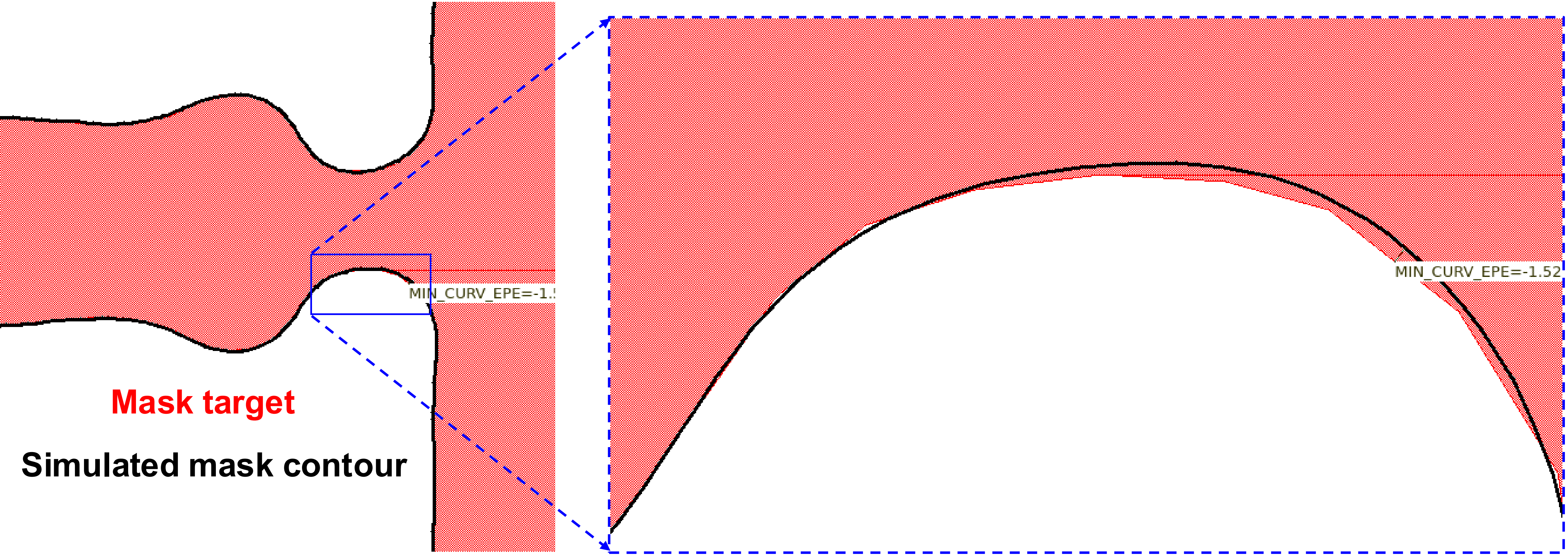






Curve OPC output can be unfriendly to MEC.
Quick custom tuning greatly reduces EPE.

Higher curvature may lead to weak convergence areas



<u>Verification results for entire layout (PLRC):</u> **Goal: abs(EPE) <= 1.0nm**

<u>For those errors w/ abs(EPE) > 1.0:</u>

→ Ave EPE offset: +0.03nm

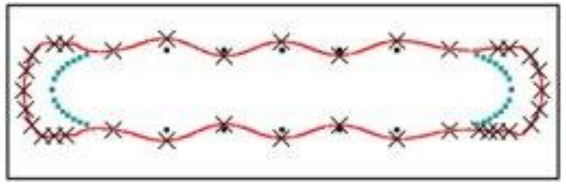
→ 95% (pos) < 1.30nm, → 95% (neg) > -1.15nm

Curve MEC output file size

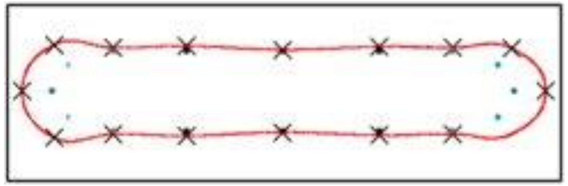
Optimization of MEC output file size

Balanced vertex density can enable 50% decrease on large designs

MEC vertex densities



Medium Vertex density

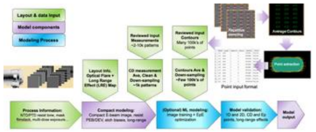


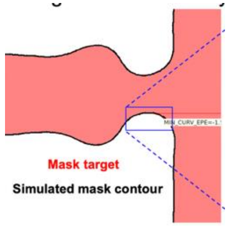
Lower Vertex density

increase/decrease

Flow Stage	Layout	File Size
MEC Input - post-OPC	#1	1,958K bytes
	#2	4,397M bytes
	#3	824K bytes
MEC Output - medium vertex density	#1	4,111K bytes
	#2	3,982M bytes
	#3	1,147K bytes
MEC Output - medium vertex density	#1	1,647K bytes
	#2	1,788M bytes
	#3	562K bytes

Summary





- Industry needs full-flow curvilinear solutions from Process Dev. to Mask write
  - Calibration data collect/analyze, mask/wafer modeling, MEC correction, MRC, verify, fracture
- Demonstrated an ML-ready MEC model data/calibration flow & accurate curvilinear MEC model results
- Applied curvilinear MEC solution to multiple layouts & validated with fabrication
- Used S-Metro to analyze the accuracy of MEC solution on a wide variety of pattern types in challenging curvilinear post-OPC layouts
- Applied intelligent vertex density to control file size with the curvilinear MEC solution

Thank You