Contour based process characterization and modeling for HVM

Kan Zhou, Wenzhan Zhou

Shanghai Huali Integrated Circuit Corp

Qijian Wan, Chunshan Du, Wenming Wu, Ao Chen, Recoo Zhang, Germain Fenger, Seshadri Rampoori

Mentor a Siemens Business

Mentor® A Siemens Business

HLMC 上海华力集成电路制造有限公司
SHANGHAI HUALI INTEGRATED CIRCUIT CORPORATION

Outline

- Introduction
- Contour extraction
- SEM image distortion correction
- Contour-based process characterization & modeling
  - ◆N-sigma roughness band
  - ◆Process window map
  - ◆3D compact resist model
- Conclusion

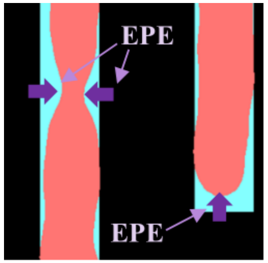
Introduction – Applications of SEM Contours

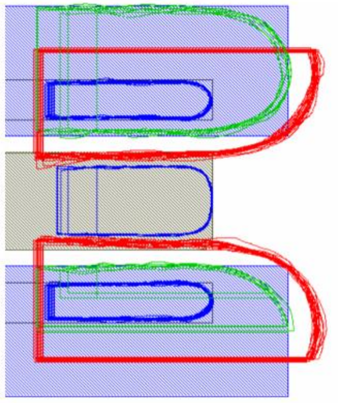
EPE measurement

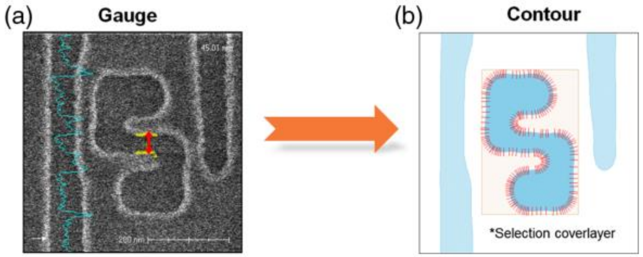
OPC modeling

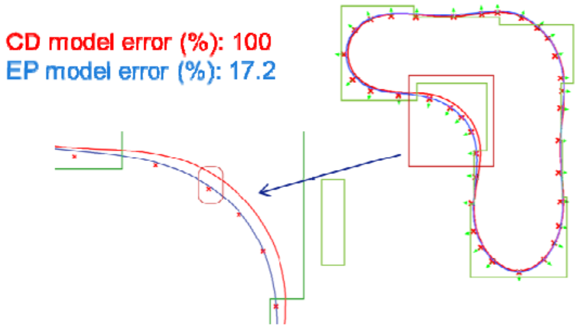
Other applications

- Process characterization
- 3D resist model
- Process monitoring
- …






(a)
Gauge
(b)
Contour
*Selection coverlayer

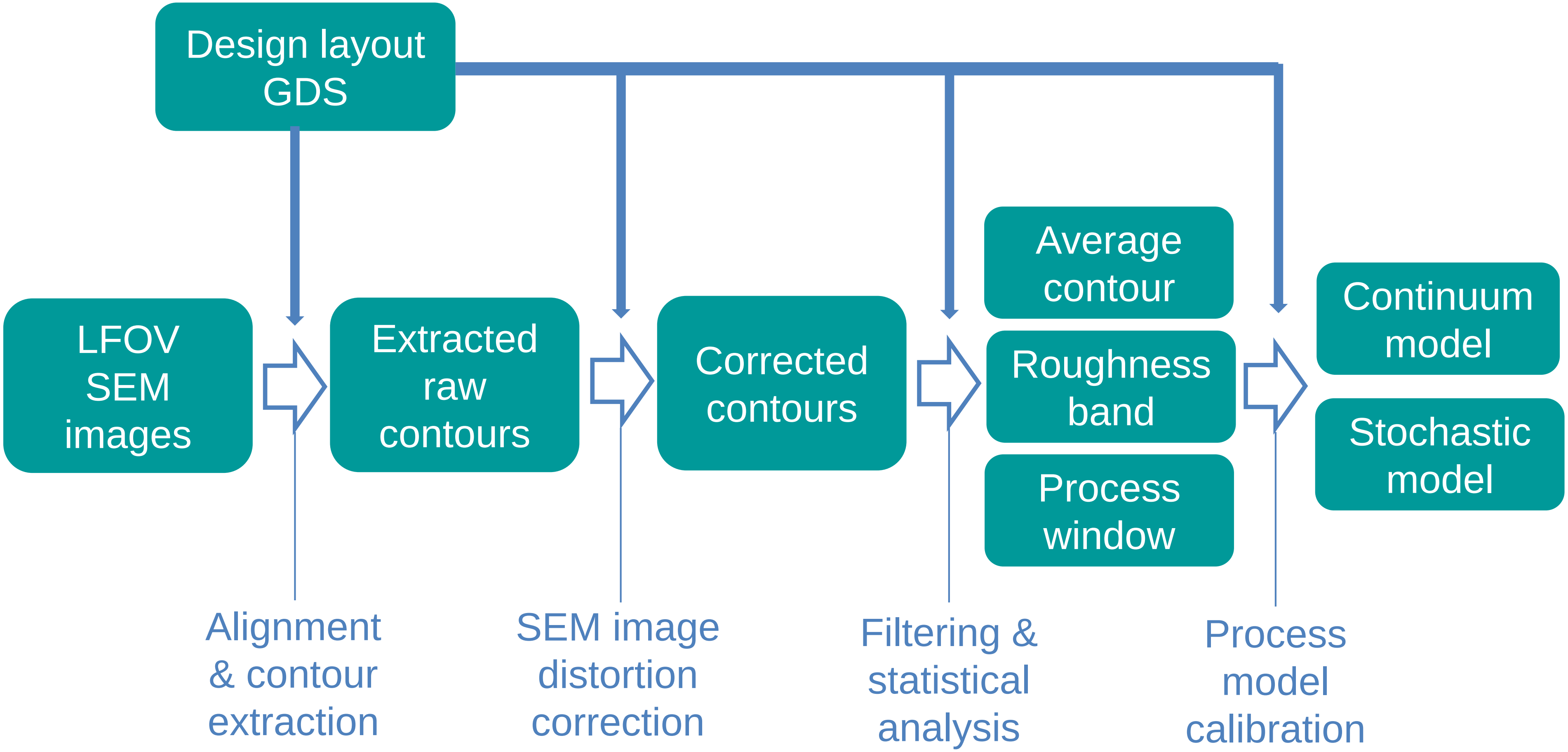

CD model error (%): 100
EP model error (%): 17.2

Y. Sato *et al*, Proc. SPIE 10959, 109590D (2019)
B. Le-Gratiet *et al*, Proc. SPIE 11325, 1132505 (2020)
F. Weisbuch *et al*, J. Micro/Nanolith. 14 (2), 021105 (2015)
Q. Zhao *et al*, Proc. SPIE 10585, 105852Q (2018)

Outline

- **Introduction**
- **Contour extraction**
- **SEM image distortion correction**
- **Contour-based process characterization & modeling**
  - ◆N-sigma roughness band
  - ◆Process window map
  - ◆3D compact resist model
- **Conclusion**

Contour Extraction & Analysis Flow



Design layout GDS

LFOV SEM images

Extracted raw contours

Corrected contours

Average contour

Roughness band

Process window

Continuum model

Stochastic model

Alignment & contour extraction

SEM image distortion correction

Filtering & statistical analysis

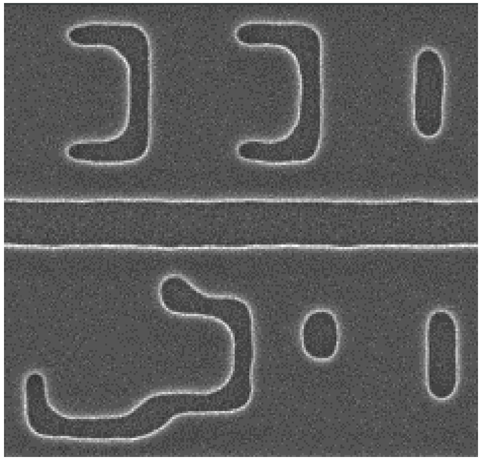
Process model calibration

Contour Extraction - Approach

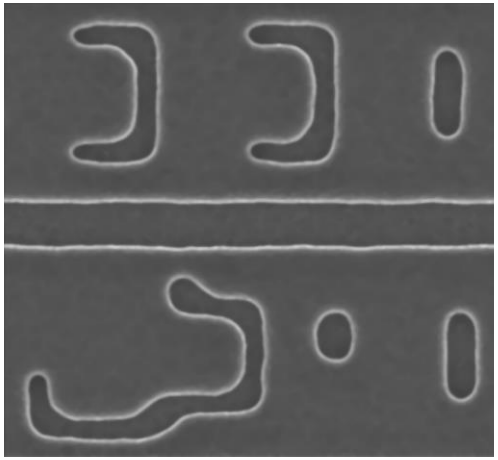
- Our contour extraction flow consists of the pre-processing, edge detection and contour formation steps.
- Different filters, such as Gaussian, Median and NL means, are used to enhance the image contrast.
- Edge detection is based on the Canny approach, with multiple thresholds enabled in case of orientation-dependent image contrast.
- Topography definition and inner/outer contour separation is assisted by the design target layout.

Contour Extraction - Results

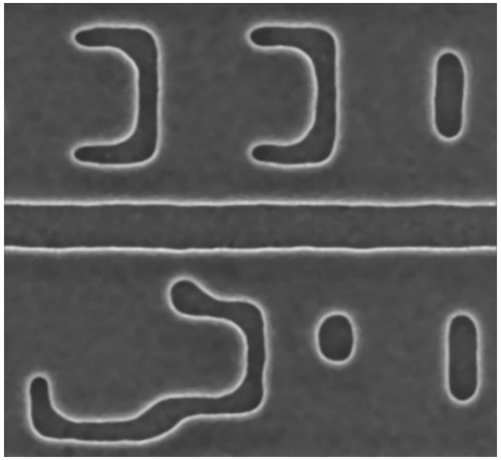
Raw image



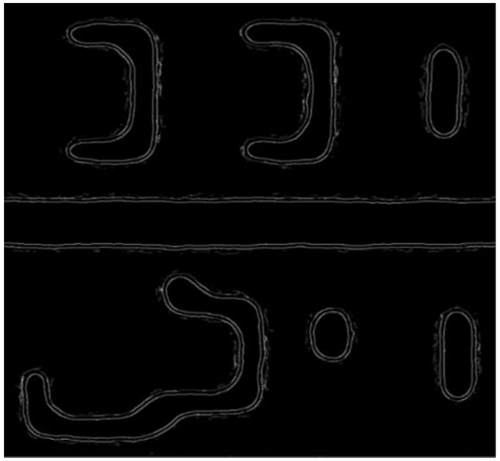
Denoising



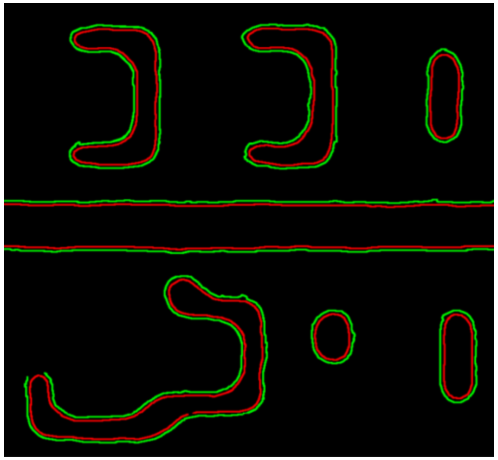
Enhancement



Edge detection



Final contours

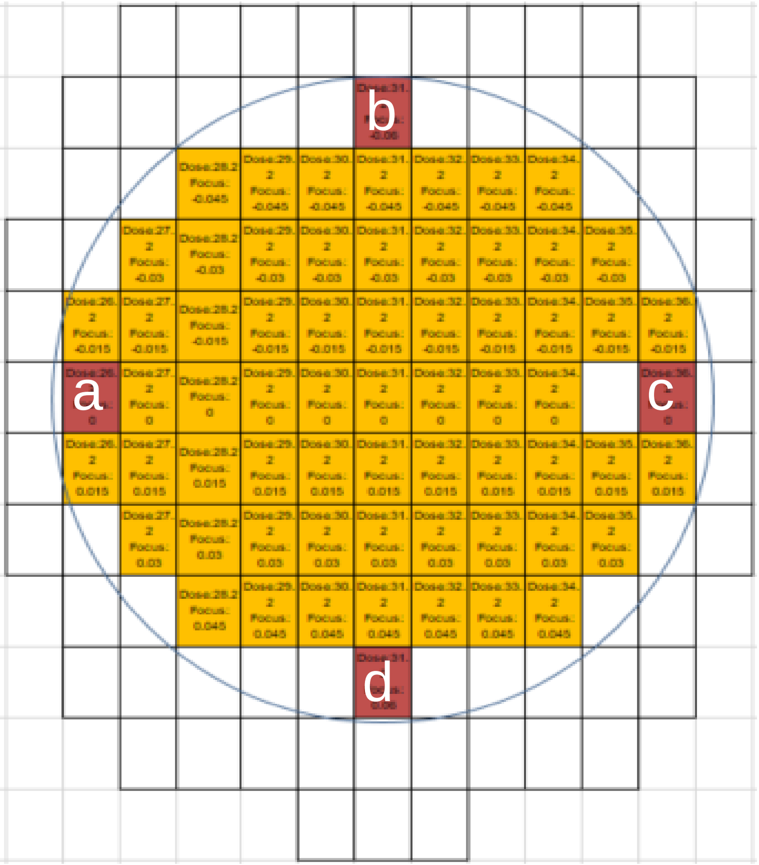


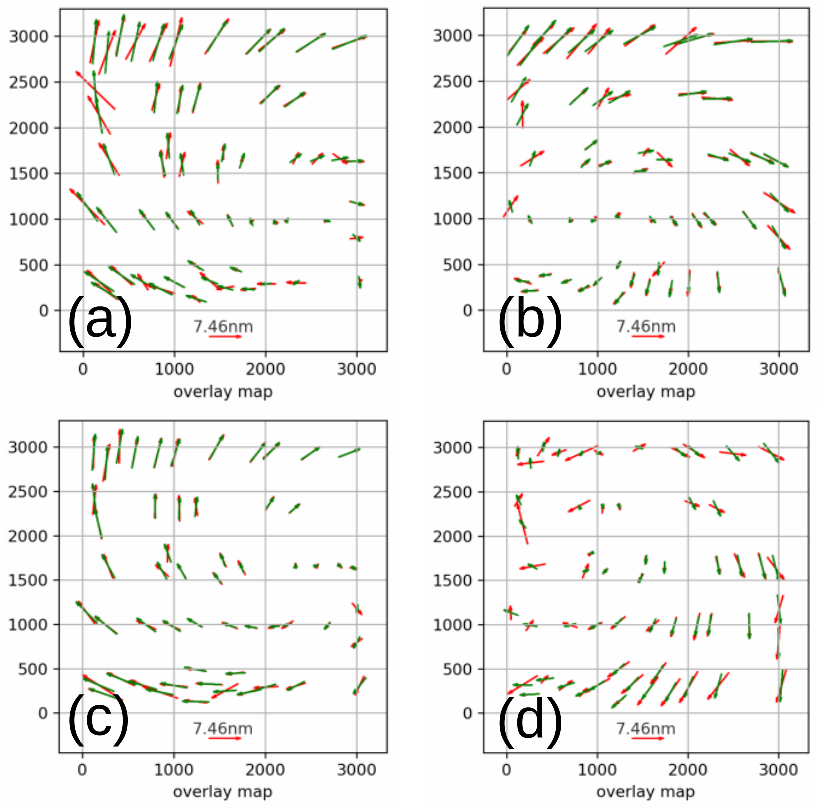
Outline

- Introduction
- Contour extraction
- SEM image distortion correction
- Contour-based process characterization & modeling
  - N-sigma roughness band
  - Process window map
  - 3D compact resist model
- Conclusion

SEM Image Distortion Correction

- **The SEM image distortion is characterized by the overlay error of as-extracted contour and design target contour within the field of view.**


b
a
c
d
Dose:28.2
Focus:
-0.045
Dose:29.2
Dose:30.2
Dose:31.2
Dose:32.2
Dose:33.2
Dose:34.2
Dose:35.2
Dose:36.2
Dose:26.2
Dose:27.2
Focus:
-0.03
-0.015
0
0.015
0.03
0.045
-0.06
0.06



SEM Image Distortion Correction

- The overlay error can be modeled, to the first approximation, as the linear combination of the errors in translation, expansion and rotation*.

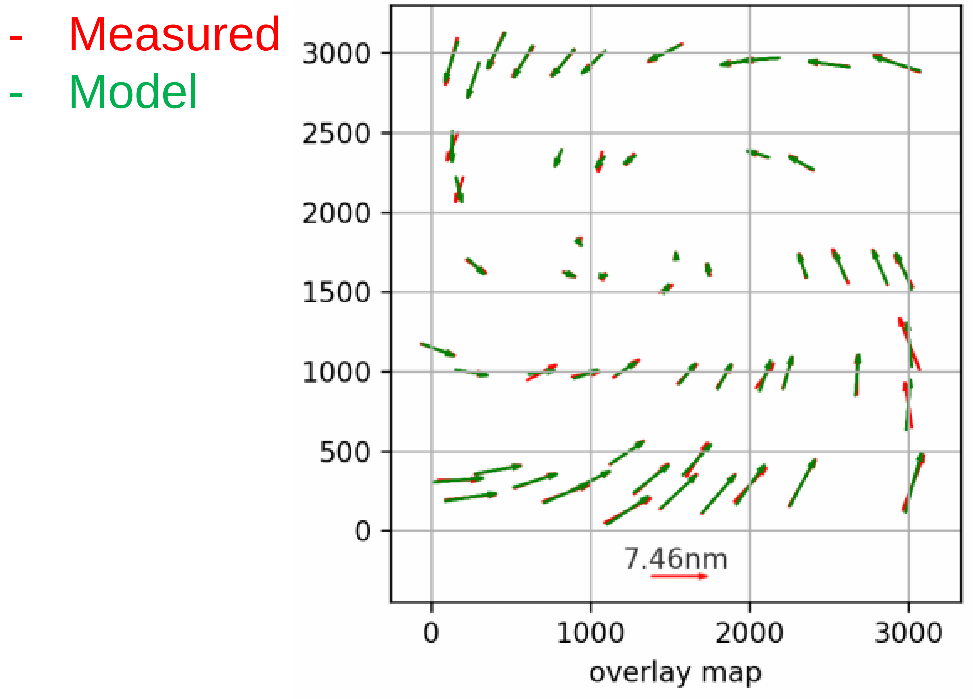
- The overlay error (dx, dy) at a given coordinate (x, y) is expressed by

$$\begin{aligned} dx &= Tx + Ex \cdot X - Rx \cdot Y \\ dy &= Ty + Ey \cdot Y + Ry \cdot X \end{aligned}$$

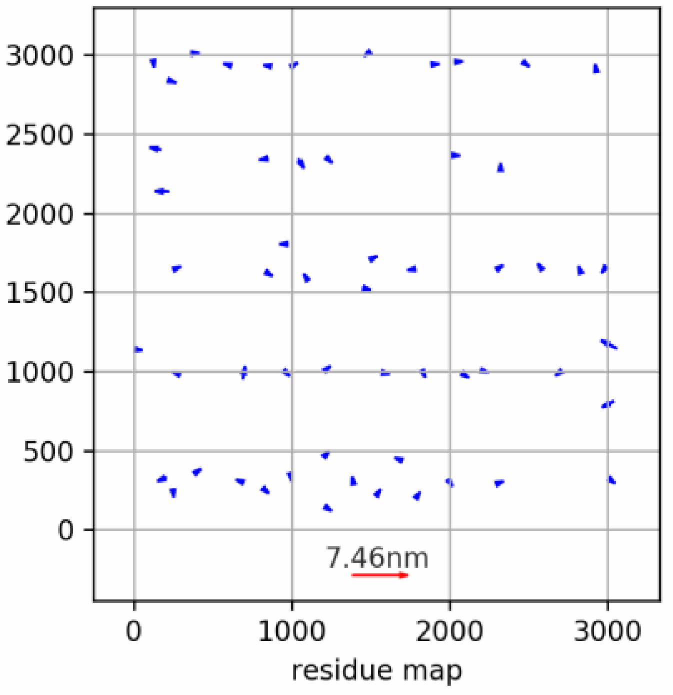
*Harm Dillen, *et al*, “CD-SEM distortion quantification for EPE metrology and contour analysis”, SPIE 10145, 1014515-1

SEM Image Distortion Correction - Results

Original overlay map



Post-correction residual error



- **The original overlay errors show a strong signature with respect to the SEM field location. The error is >8 nm at the field edge.**
- **The overlay errors were well compensated by the simple linear model with six parameters.**

Outline

- Introduction
- Contour extraction
- SEM image distortion correction
- **Contour-based process characterization & modeling**
    - ◆N-sigma roughness band
    - ◆Process window map
    - ◆3D compact resist model
- Conclusion

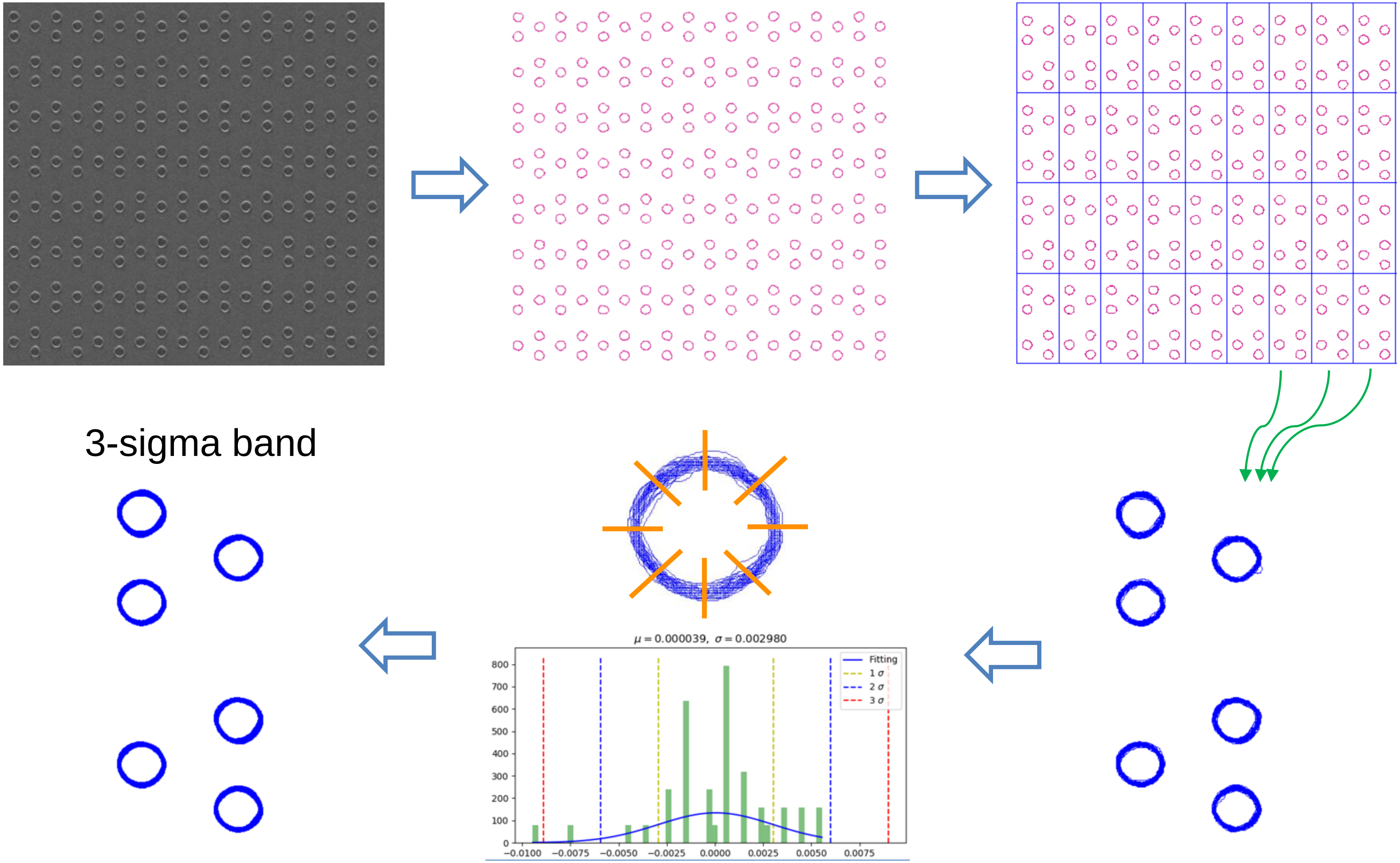
N-Sigma Roughness Band - Motivation

- **Large FOV allows measurement of multiple repeating cells, which provide the local pattern roughness information.**

- **Extracted contours of the unit cell can be cut and stacked, followed by statistical analysis to generate the N-sigma roughness band.**

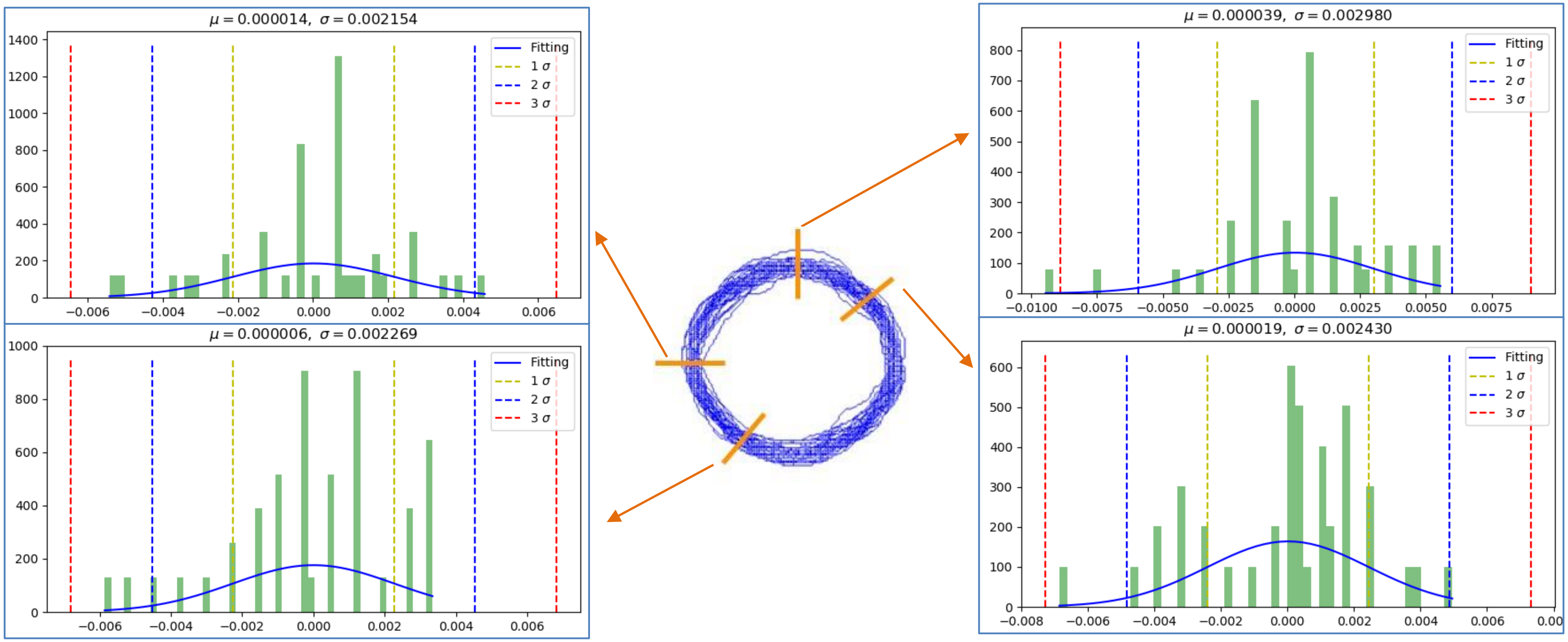
- **The N-sigma roughness band represents the stochastic process variation, which should be considered for the EPE budge analysis.**

N-Sigma Roughness Band - Flow


$\mu = 0.000039,\ \sigma = 0.002980$
Fitting
1 σ
2 σ
3 σ
800
700
600
500
400
300
200
100
0
−0.0100
−0.0075
−0.0050
−0.0025
0.0000
0.0025
0.0050
0.0075

3-sigma band

N-Sigma Roughness Band - Results



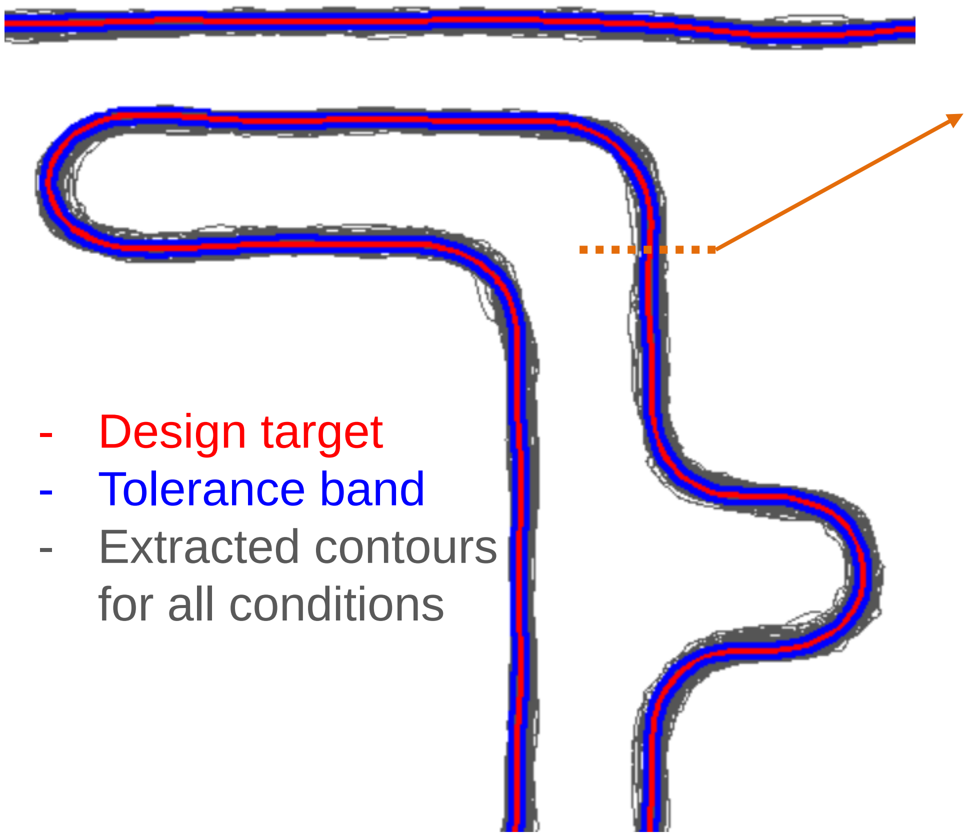
- **Statistical distribution histograms for different cutlines are demonstrated. The data were fit to normal distribution for this case.**

Contour-based PW Analysis - Motivation

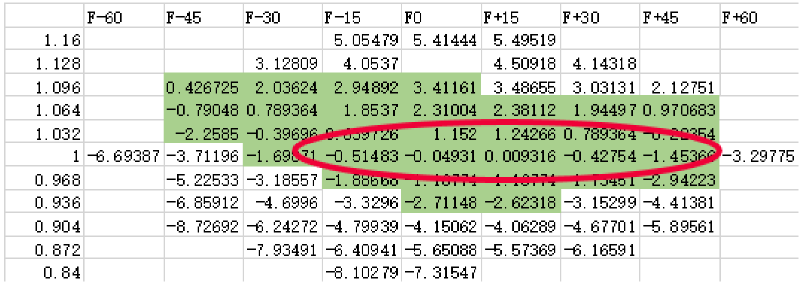
- Traditional CD-based process window (PW) is calculated with reference to a CD target and tolerance.

- Contour-based PW analysis is more than increased sampling sites:
  - PW can be calculated where CD measurement is not possible, such as an isolated line end.
  - PW calculation is EPE based, thereby taking the pattern shift error into consideration.
  - Variable tolerance band can be defined to capture the process window limiter that leads to potential failure.

Contour-based PW Analysis - Approach



- Design target
- Tolerance band
- Extracted contours for all conditions



	F-60	F-45	F-30	F-15	F0	F+15	F+30	F+45	F+60
1.16				5.05479	5.41444	5.49519			
1.128			3.12809	4.0537		4.50918	4.14318		
1.096		0.426725	2.03624	2.94892	3.41161	3.48655	3.03131	2.12751	
1.064		-0.79048	0.789364	1.8537	2.31004	2.38112	1.94497	0.970683	
1.032		-2.2585	-0.39696	0.659726	1.152	1.24266	0.789364	-0.22354	
1	-6.69387	-3.71196	-1.69671	-0.51483	-0.04931	0.009316	-0.42754	-1.45366	-3.29775
0.968		-5.22533	-3.18557	-1.88668	-1.10774	-1.10774	-1.15451	-2.94223	
0.936		-6.85912	-4.6996	-3.3296	-2.71148	-2.62318	-3.15299	-4.41381	
0.904		-8.72692	-6.24272	-4.79939	-4.15062	-4.06289	-4.67701	-5.89561	
0.872			-7.93491	-6.40941	-5.65088	-5.57369	-6.16591		
0.84				-8.10279	-7.31547				

For each sampling site on the design target, the process window is analyzed based on the EPE's and tolerance along the perpendicular cutline.

Contour-based FEM Analysis - Prototype

EPE measurement for different PW condition

↓

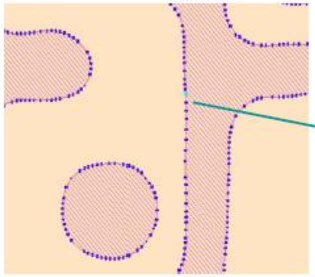
Target contour & tolerance band definition

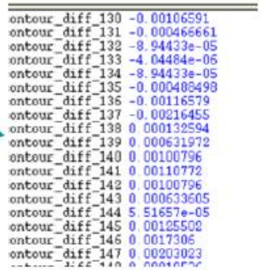
↓

Process Window Analysis

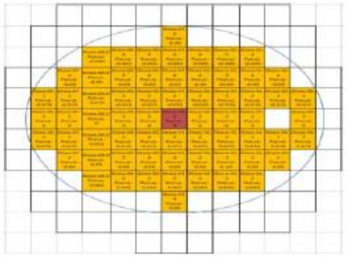
↓

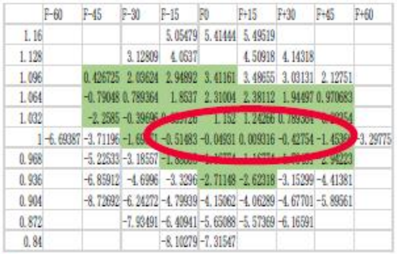
Bossung/BF | DOF | EL



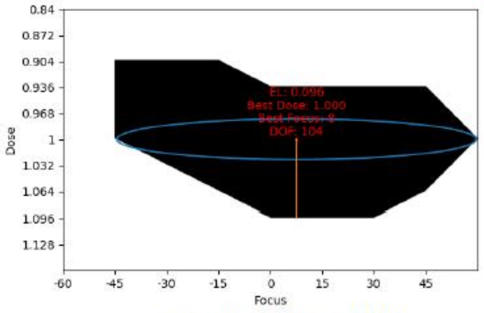


```
ontour_diff_130 -0.00106591
ontour_diff_131 -0.000466661
ontour_diff_132 -8.94433e-05
ontour_diff_133 -4.04484e-06
ontour_diff_134 -8.94433e-05
ontour_diff_135 -0.000488498
ontour_diff_136 -0.00116579
ontour_diff_137 -0.00216455
ontour_diff_138 0.000132594
ontour_diff_139 0.000631972
ontour_diff_140 0.00100796
ontour_diff_141 0.00110772
ontour_diff_142 0.00100796
ontour_diff_143 0.000633605
ontour_diff_144 5.51657e-05
ontour_diff_145 0.00125502
ontour_diff_146 0.0017306
ontour_diff_147 0.00203023
```

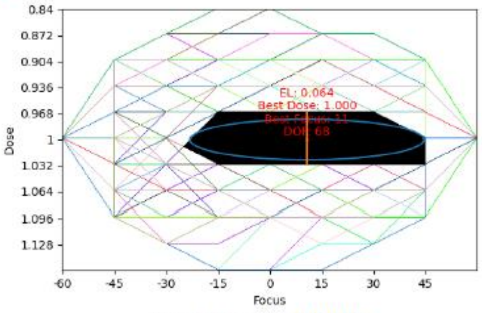




	F-60	F-45	F-30	F-15	F0	F+15	F+30	F+45	F+60
1.16				5.05479	5.41444	5.49519			
1.128			3.12809	4.0537		4.50918	4.14318		
1.096		0.426725	2.03624	2.94892	3.41161	3.48655	3.03131	2.12751	
1.064		-0.79048	0.789364	1.8537	2.31004	2.38112	1.94497	0.970683	
1.032		-2.2585	-0.39696	[illegible]	1.152	1.24266	[illegible]	[illegible]	
1	-6.69387	-3.71196	[illegible]	-0.51483	-0.04931	0.009316	-0.42754	[illegible]	-3.29775
0.968		-5.22533	-3.18557	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	
0.936		-6.85912	-4.6996	-3.3296	-2.71148	-2.62318	-3.15299	-4.41381	
0.904		-8.72692	-6.24272	-4.79939	-4.15062	-4.06289	-4.67701	-5.89561	
0.872			-7.93491	-6.40941	-5.65088	-5.57369	-6.16591		
0.84				-8.10279	-7.31547				



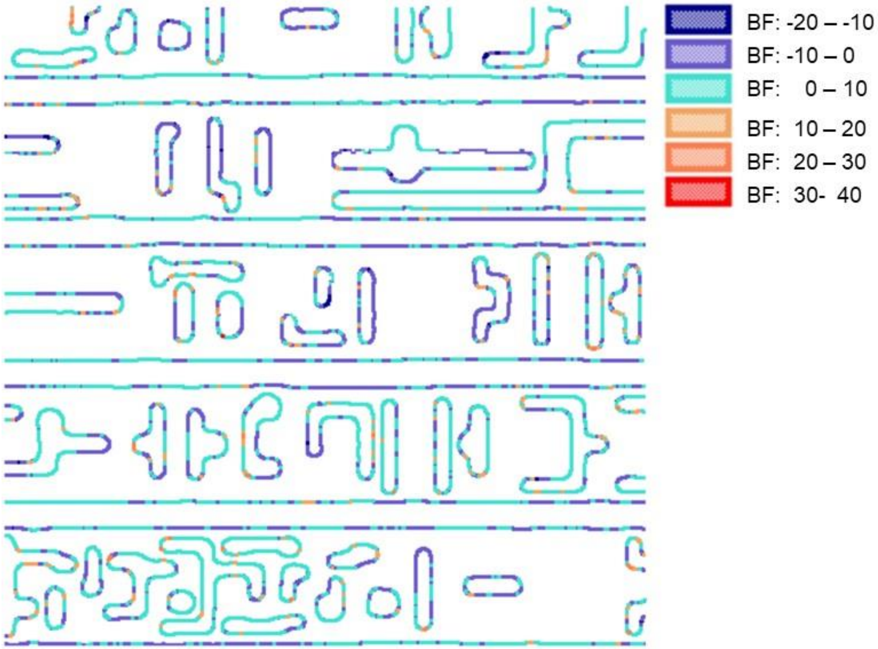
Single-Site PWA



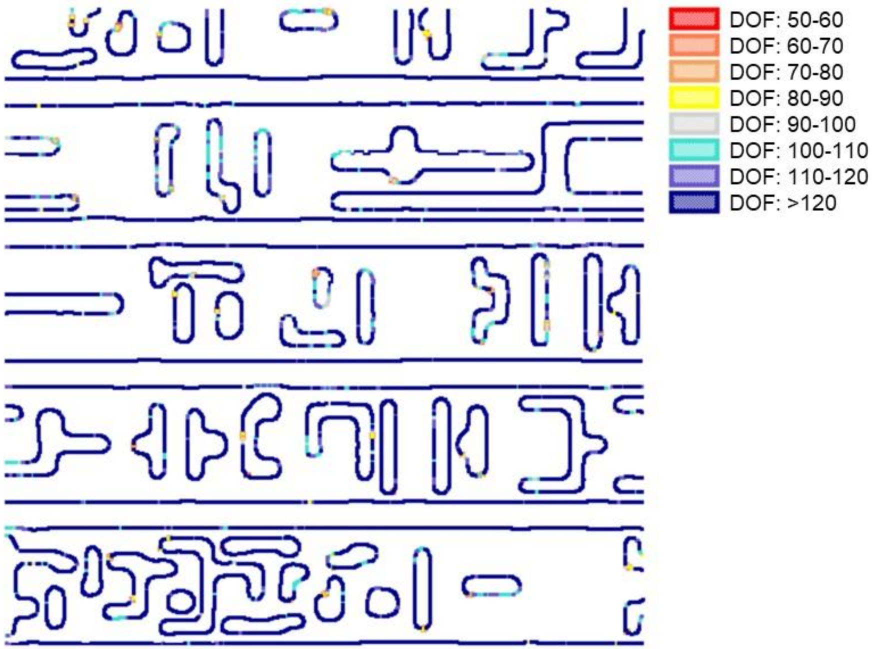
Common PWA

Contour-based PW Analysis - Results

Best focus map

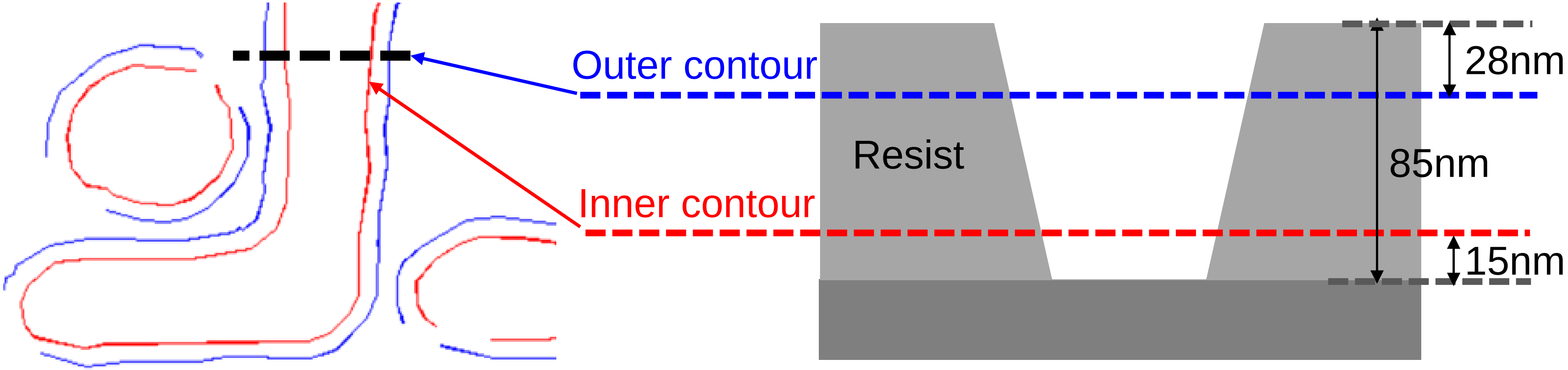

BF: -20 – -10
BF: -10 – 0
BF: 0 – 10
BF: 10 – 20
BF: 20 – 30
BF: 30- 40

DOF map


DOF: 50-60
DOF: 60-70
DOF: 70-80
DOF: 80-90
DOF: 90-100
DOF: 100-110
DOF: 110-120
DOF: >120

- **The calculated best focus and DOF color maps illustrate accurately where the process window limiters are located.**

3D Compact Resist Model - Approach

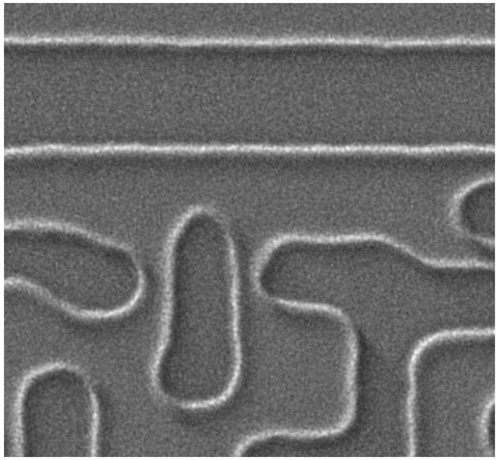

Outer contour
Inner contour
Resist
28nm
85nm
15nm

- **The inner and outer contours correspond to different resist heights, providing resist profile information.**

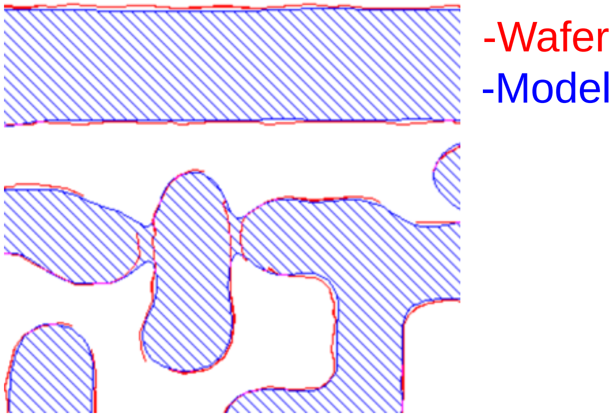
- **The inner and outer contours from the same SEM images can be used to calibrate 3D compact resist model.**

3D Compact Resist Model - Results

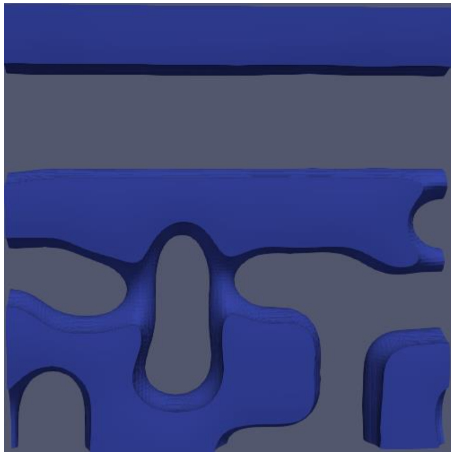
Top-down
SEM image



Outer contour from 3D
compact resist model



Rigorous simulation



- The 3D compact resist model we calibrated predicts bridging at the outer contour resist height, while the top-down SEM image and extracted outer contour do not show it.
- Rigorous simulation confirms evident resist top loss at the tip-to-side location, indicating the 3D compact resist model can capture top loss related hotspot.

Outline

- Introduction
- Contour extraction
- SEM image distortion correction
- Contour-based process characterization & modeling
  - ◆N-sigma roughness band
  - ◆Process window map
  - ◆3D compact resist model
- Conclusion

Conclusion

- Contours were extracted from the SEM images with good edge fidelity by using improved Canny edge detector.

- The LFOV SEM image distortion was well compensated by a linear model with six parameters.

- Contour-based applications including N-sigma roughness band, contour-based process window analysis and 3D compact resist model were demonstrated.