Layout simulation for directed self-assembly with chemo-epitaxy methodology

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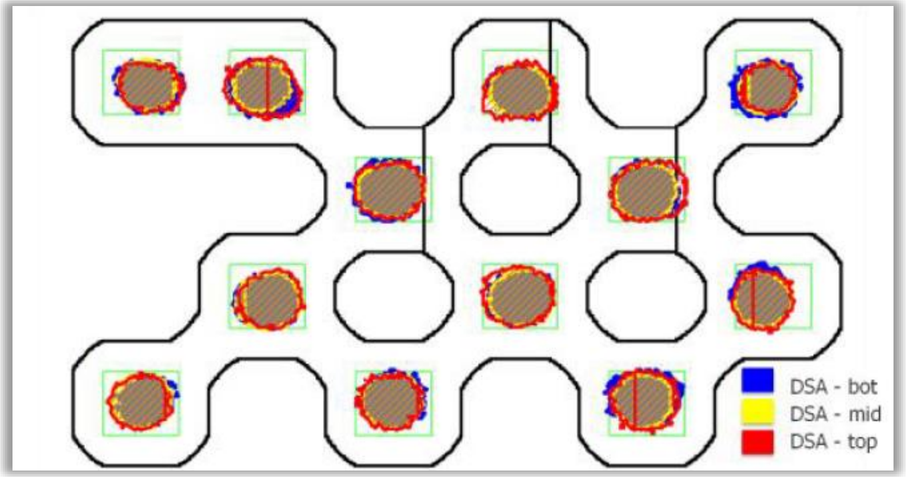
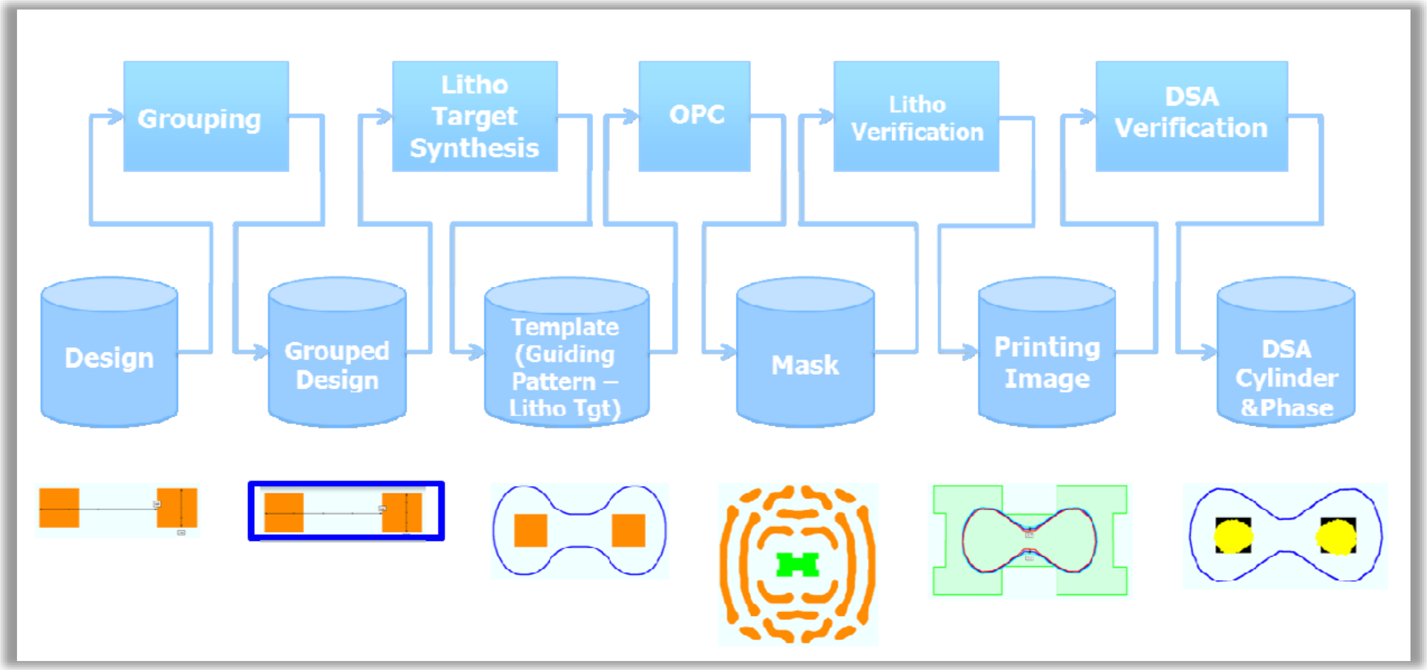
Outline

- Motivation for a rigorous simulation engine for DSA chemo-epitaxy patterning processes.
- Contact hole with EUV rectification and DUV pitch multiplication.
- Line Space with EUV rectification and DUV pitch multiplication.
- Design window discussion with simulation results.

Siemens can simulate DSA with grapho-epitaxy technology

DSA technology with grapho-epitaxy needs co-optimization among materials, design and lithography.
Not mature enough by the time EUV lithography becomes prevalent.



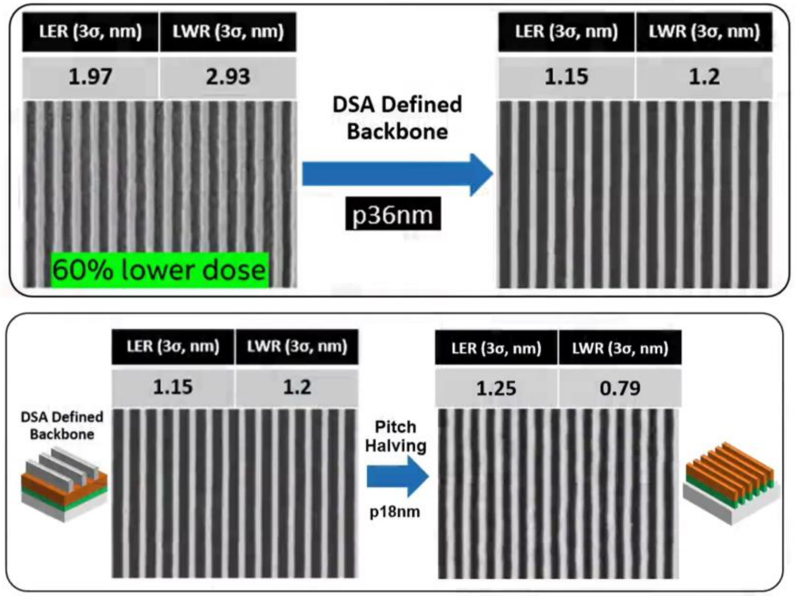


Ma et al, Challenges and opportunities in applying grapho-epitaxy DSA lithography to metal cut and contact/via applications, SPIE 2014, 9231, 92310T
Ma et al, Directed Self Assembly (DSA) compliant flow with immersion lithography – from material to design and patterning, SPIE 2016, 9777 97770N

Industry has shown that DSA with chemo-epitaxy can improve tight pitch Line-Space and Contact Hole pattern fidelity

Logic:

LER can be improved in EUV rectification P36nm, and maintained after pitch halving to P18nm.



LER (3σ, nm)	LWR (3σ, nm)
1.97	2.93

LER (3σ, nm)	LWR (3σ, nm)
1.15	1.2

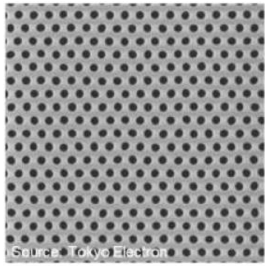
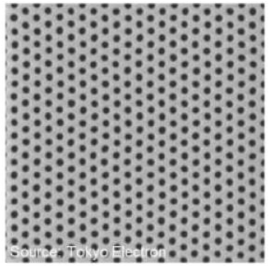
LER (3σ, nm)	LWR (3σ, nm)
1.15	1.2

LER (3σ, nm)	LWR (3σ, nm)
1.25	0.79

Singh, Continuing Moore's Law with next-gen DSA, SPIE 2023 12497-29

Memory:

9x and 12x multiplication to reach P40 nm and P35 nm contact hole with DUV lithography.

	Lo 40nm	Lo 35nm
	9 multiplication	12 multiplication
SEM picture as SOC etch		
CD	20.9nm	17.5nm
LCDU (3σ)	1.52nm (7.3%)	1.66nm (9.5%)
Placement Error (3σ)	2.76nm (13.2%)	2.70nm (15.4%)

Muramatsu et al, Pattern fidelity improvement of DSA hole patterns, SPIE 2023 12497, 124970J

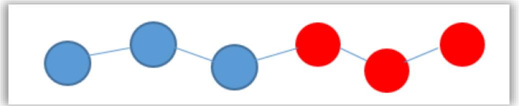
Available simulation methods:

- Coarse grained molecular dynamic simulation (Cornell, *Soft Matter* 2018)
- Coarse grained Monte Carlo simulation (U of Chicago, Macromolecular 2008)

SIEMENS

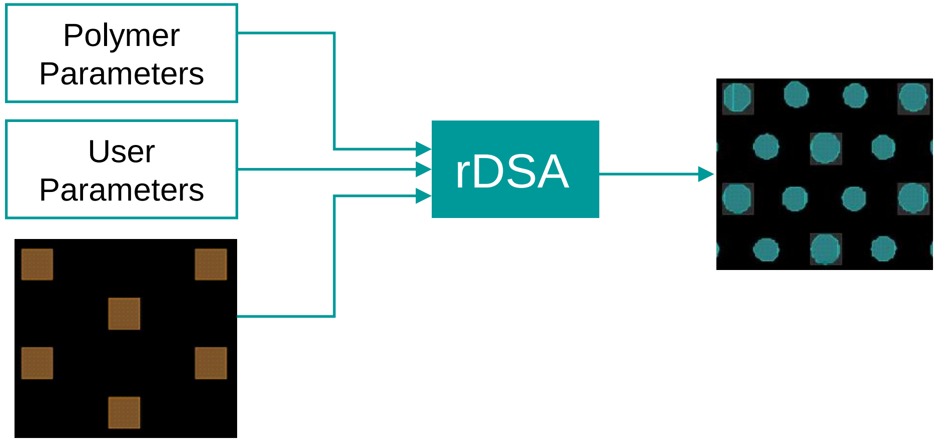
Calibre rDSA, SEMSuite and OPCVerify for Simulation and SEM image analysis

Calibre ® rDSA module provides a functionality to run rigorous full physics simulations of the DSA process. Monte Carlo simulations of a coarse grain model can describe effects of patterned substrates and complex geometries with relatively modest computational effort.



Bead-Spring representation of a block-copolymer chain

*Detcheverry et al, Monte Carlo Simulations of a Coarse Grain model for Block Copolymers and Nanocomposites, **Macromolecules** 2008, 41, 4989*

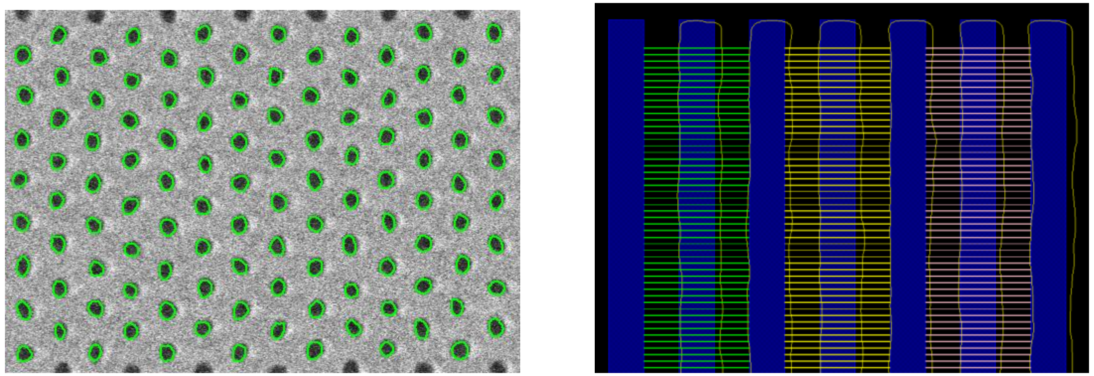


Polymer Parameters

User Parameters

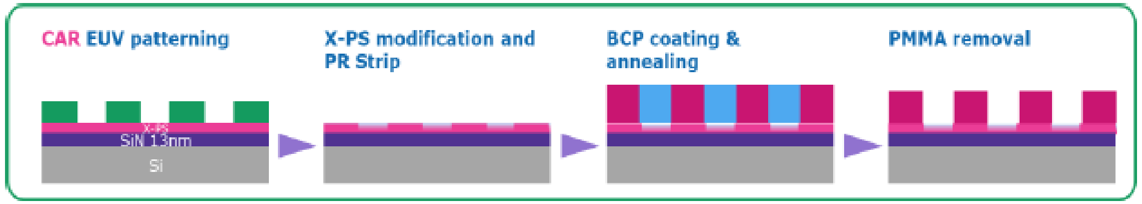
rDSA

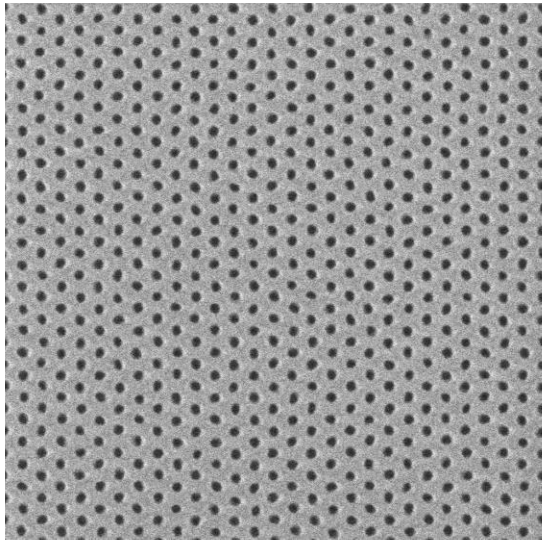
Calibre® SEMSuite$^{\text{TM}}$ was utilized to extract contours from each individual SEM images. Calibre® OPCVerify$^{\text{TM}}$ was used to analyze the statistics of the extracted contours and simulated contours for LER, LCDU, and PPE.



EUV rectification for Contact Hole patterns P34 c2c 1x

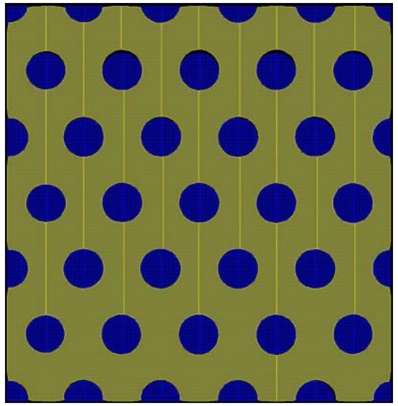
Imec mild etch flow rectification





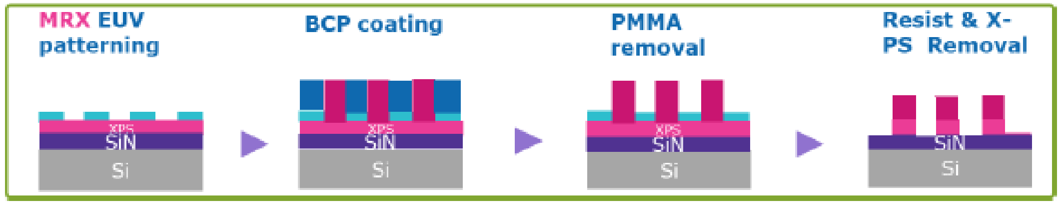
CD = 13.7 nm
LCDU = 2.0 nm (3σ)
PPE = 2.3 nm

Blue: guiding pattern
Yellow: DSA pattern

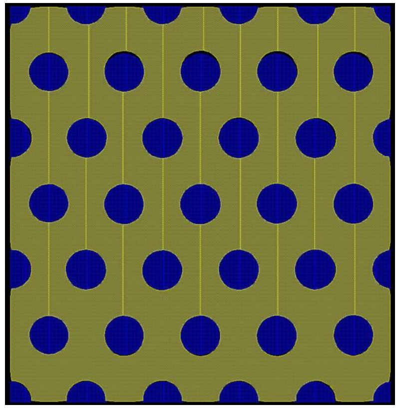


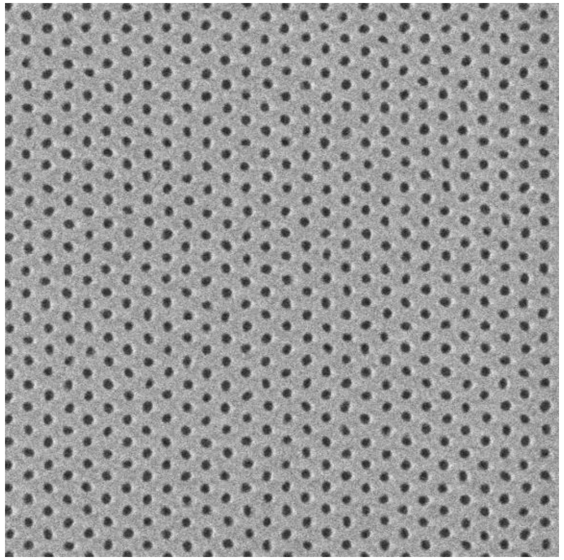
SEM image is taken after PMMA removal, and before pattern transfer.

All track flow



CD = 13.4 nm
LCDU = 2.5 nm (3σ)
PPE = 2.06 nm





SEM image is taken after PMMA removal, and before pattern transfer.

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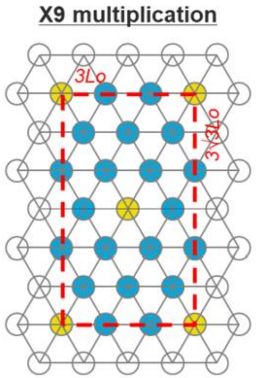
HEX-CH DUV M-flow 9x Pitch multiplication 120nm to Pitch 40nm

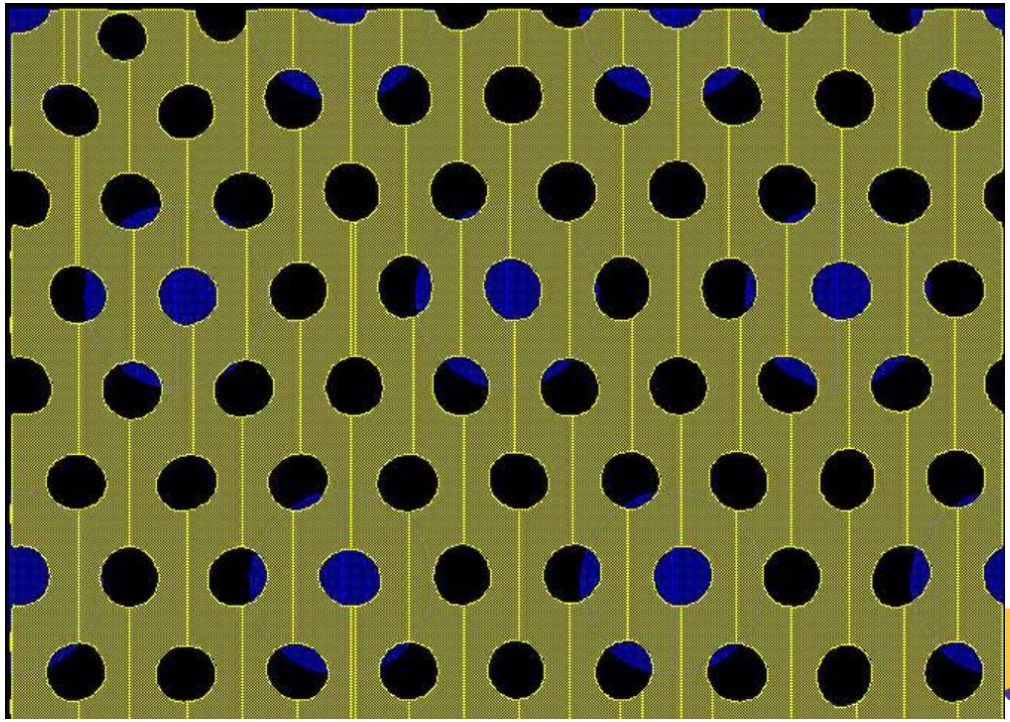

NL Coating
PR Patterning
NL Etching
Resist Stripping
PS-brush coating
BCP
PMMA Wet Develop

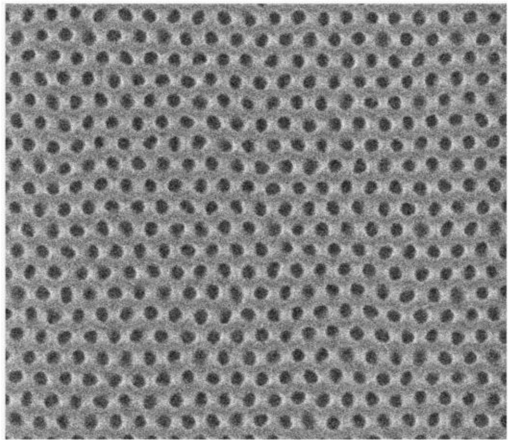
Muramatsu et al, *Hexagonal arrays of contact holes with chemo-epitaxial DSA*, SPIE 12054, 1205402 (2022)



Blue: guiding pattern
Yellow: DSA pattern

Guiding Pattern
P=120nm
CD=66 nm

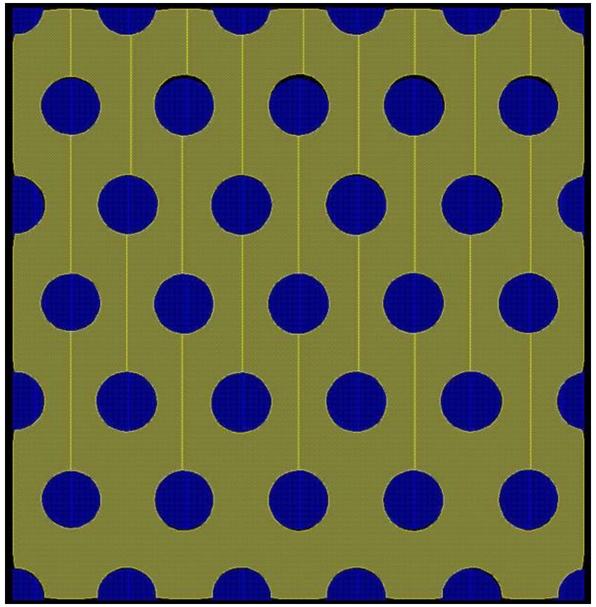




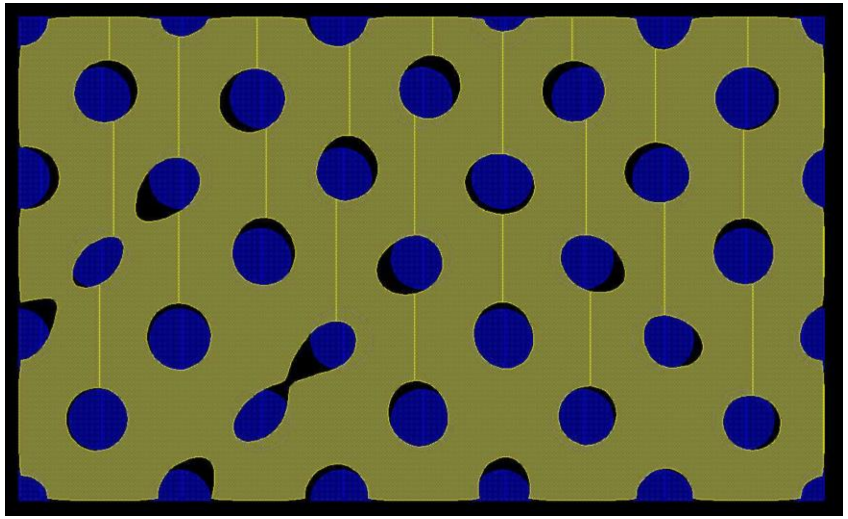
CD = 19.4 nm
LCDU = 3.3 nm (3σ)
PPE: 2.76 nm

SEM image is taken after PMMA removal,
and before pattern transfer.

Simulation of Contact Hole with hexagonal vs orthogonal arrangement



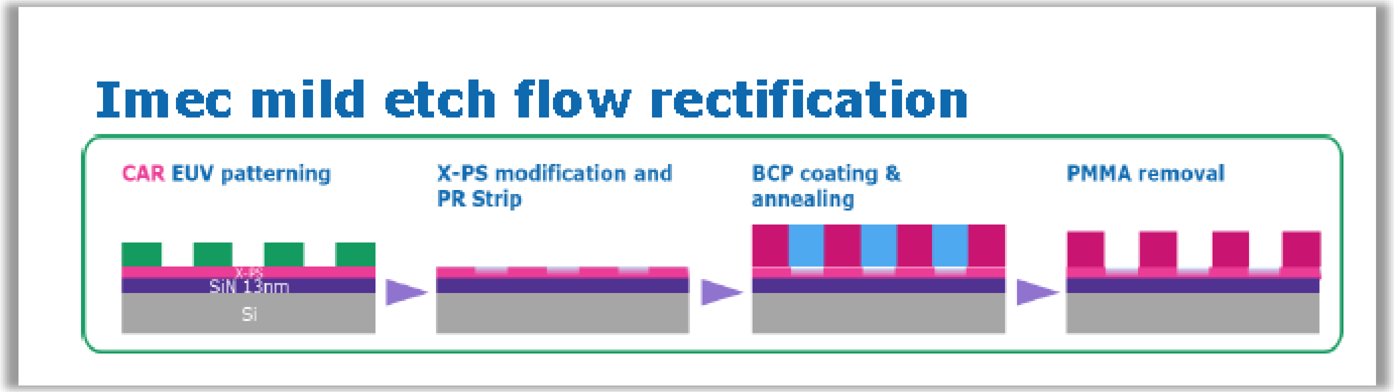
	HEX	orthogonal
CD (nm)	18.05	18.36
Circularity	0.995	0.956
LCDU (3σ nm)	0.68	4.76
PPE (nm)	0.62	2.3

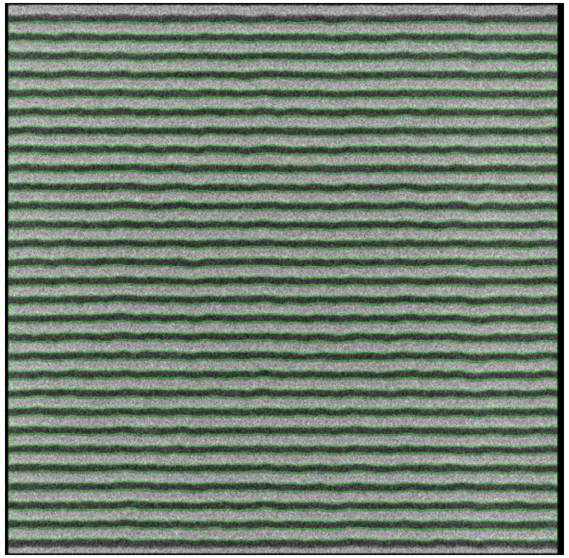


$$\text{Circularity} = \frac{4\pi \text{ x Area}}{\text{Perimeter}^2}$$

With the same composition and same Pitch (34 nm) and L0, orthogonal arrangement shows much worse contact hole formation in terms circularity, LCDU and PPE.

EUV rectification for Line Space patterns



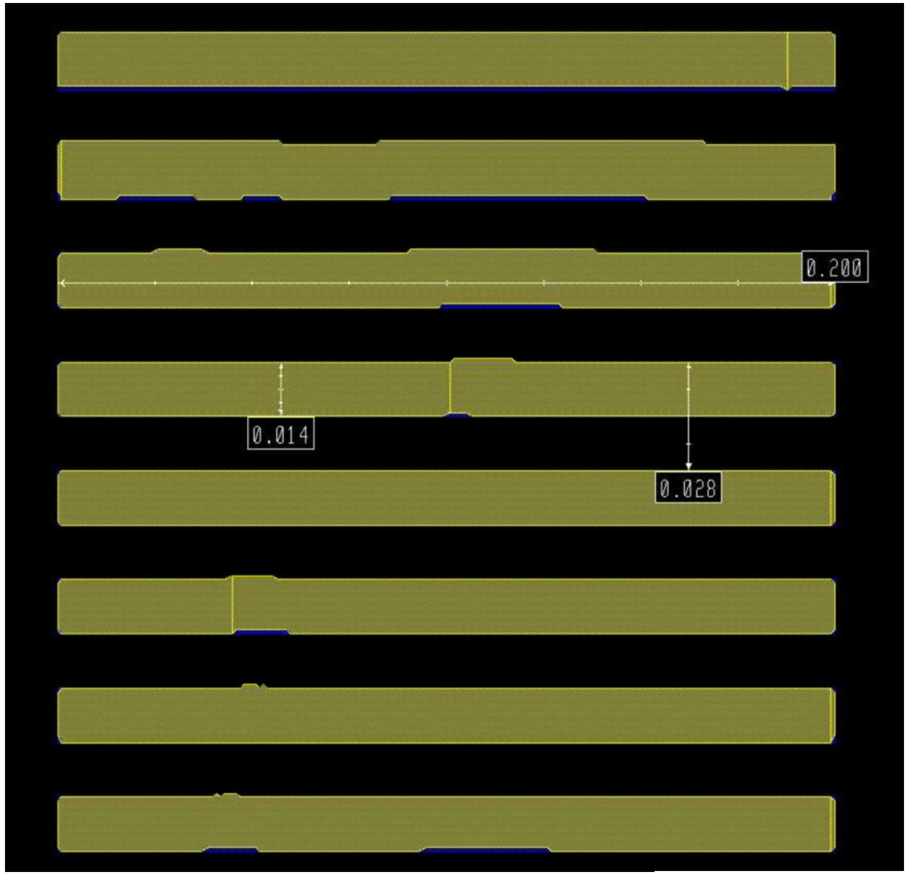


SEM image is taken after PMMA removal, and before pattern transfer.

CAR_mild etch flow P28nm L/S Experiment:

- CD = 16.6 nm
- LER= 2.43 nm (3σ)

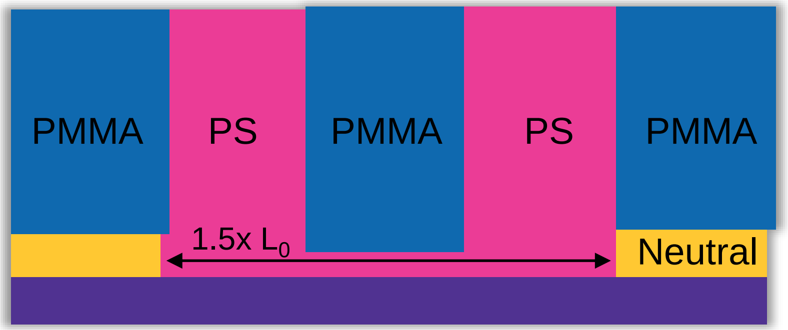
Blue: guiding pattern
Yellow: DSA pattern

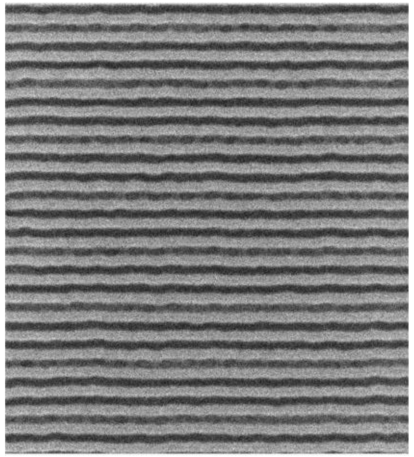


DUV 3x pitch multiplication for Line Space patterns – SMART flow

SMART flow: L/S equivalent of M-flow

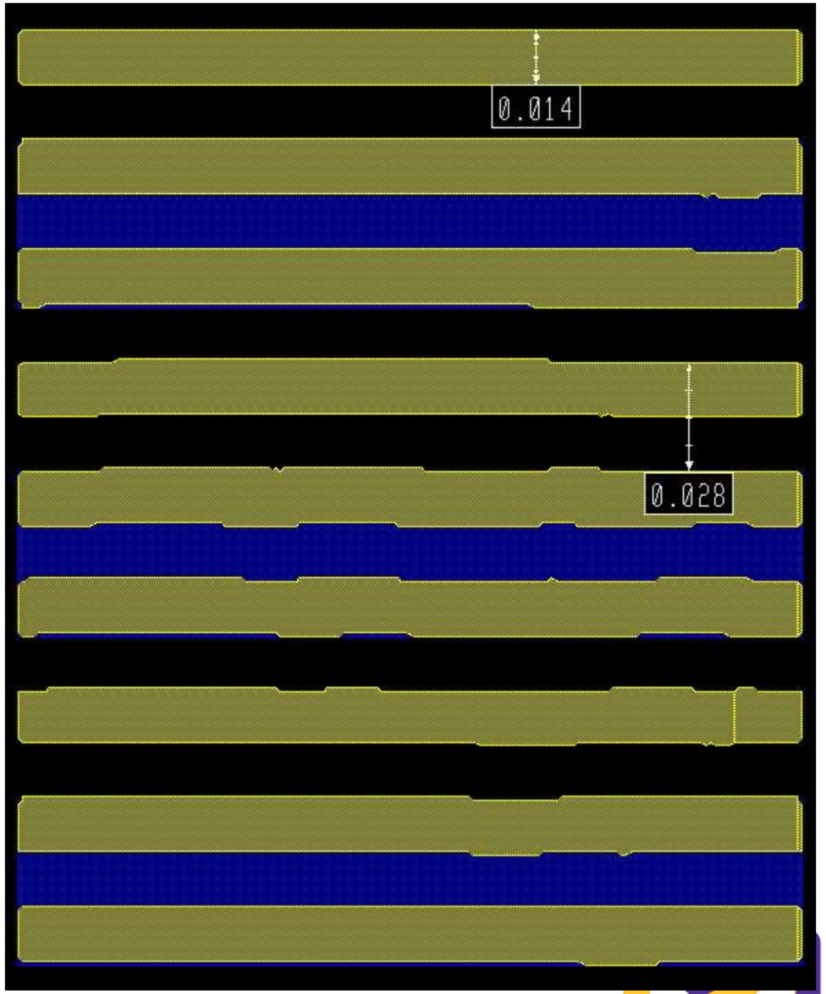
Pitch 84nm on ArFi process, ideal guiding pattern CD for line/space is 42/42nm.



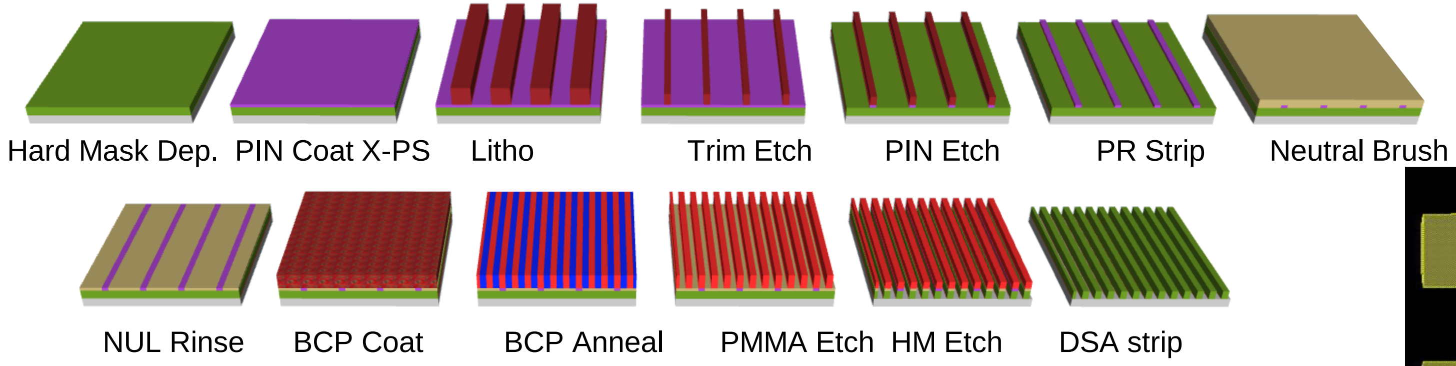


SEM image is taken after PMMA removal, and before pattern transfer.

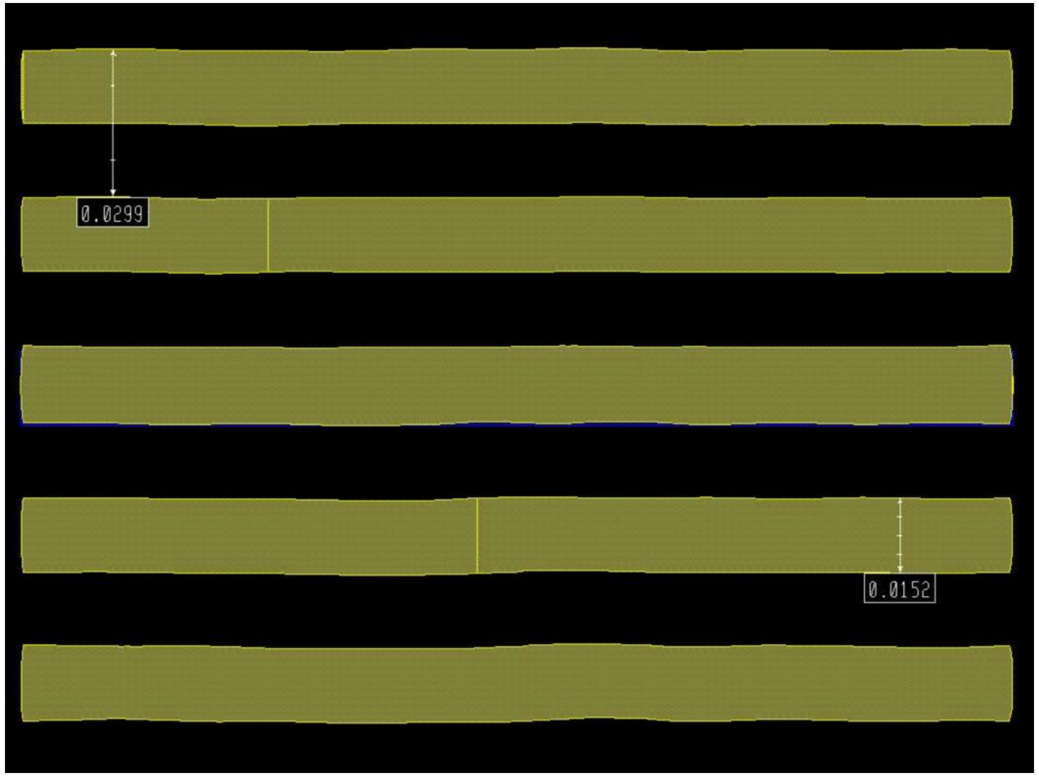
Blue: guiding pattern
Yellow: DSA pattern



DUV 3x pitch multiplication for Line Space patterns – LiNe flow

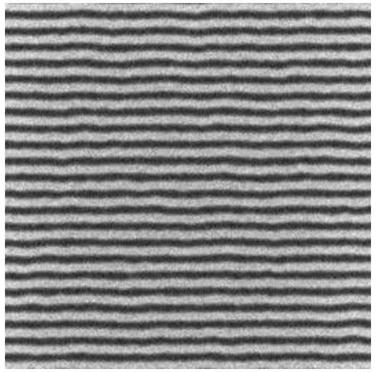


Blue: guiding pattern
Yellow: DSA pattern



LiNe Flow:

Pitch 90nm on ArFi, guiding pattern CD is 15nm.

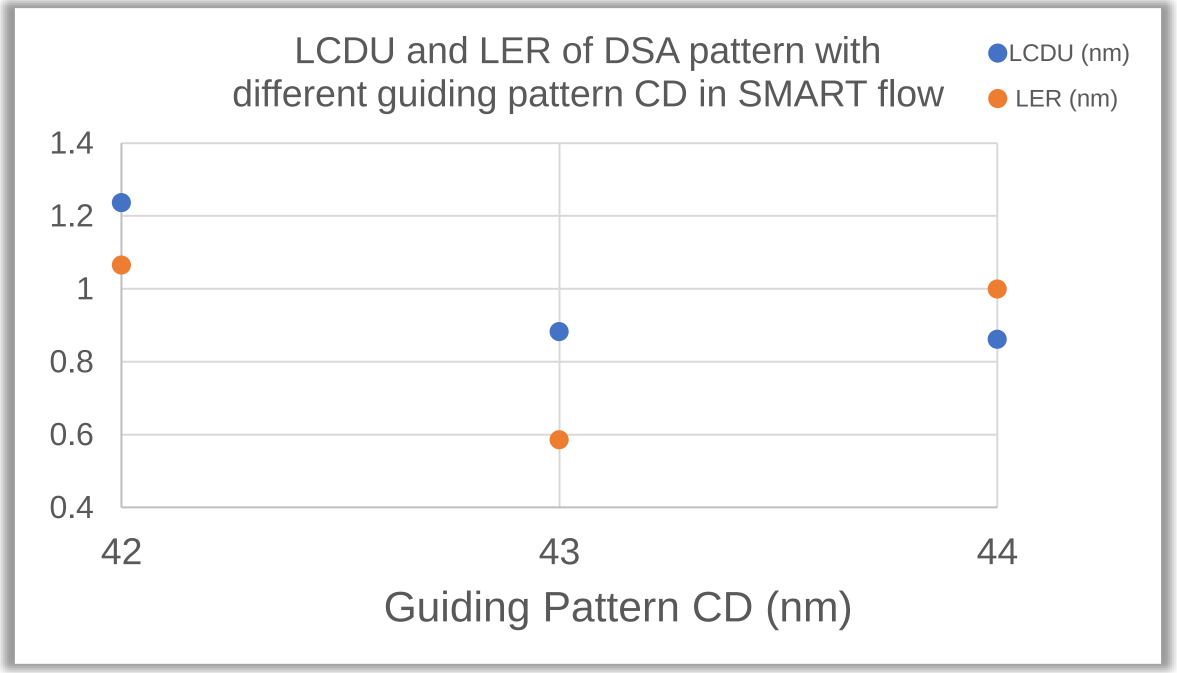


SEM image is taken after PMMA removal, and before pattern transfer.

Simulation shows DSA patterns are stable with varying guiding pattern CD

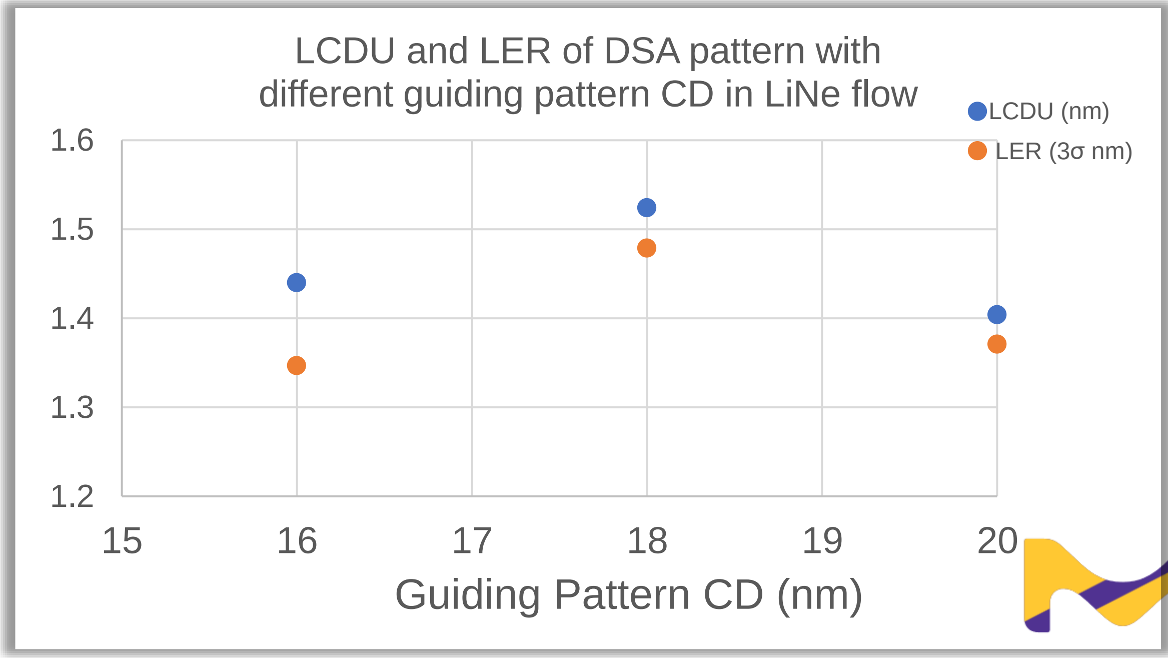
SMART flow: P84 3x → P28nm

Guiding Pattern CD (nm)	42	43	44
DSA CD	13.94	13.92	13.95
DSA LCDU (3σ)	1.23	0.88	0.86
DSA LER (3σ)	1.06	0.59	1.00



LiNe flow: P90 3x → P30nm

Guiding Pattern CD (nm)	16	18	20
DSA CD	15.01	14.95	14.99
DSA LCDU (3σ)	1.44	1.52	1.40
DSA LER (3σ)	1.35	1.48	1.37



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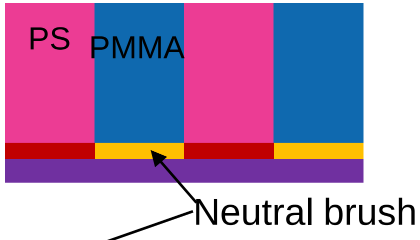
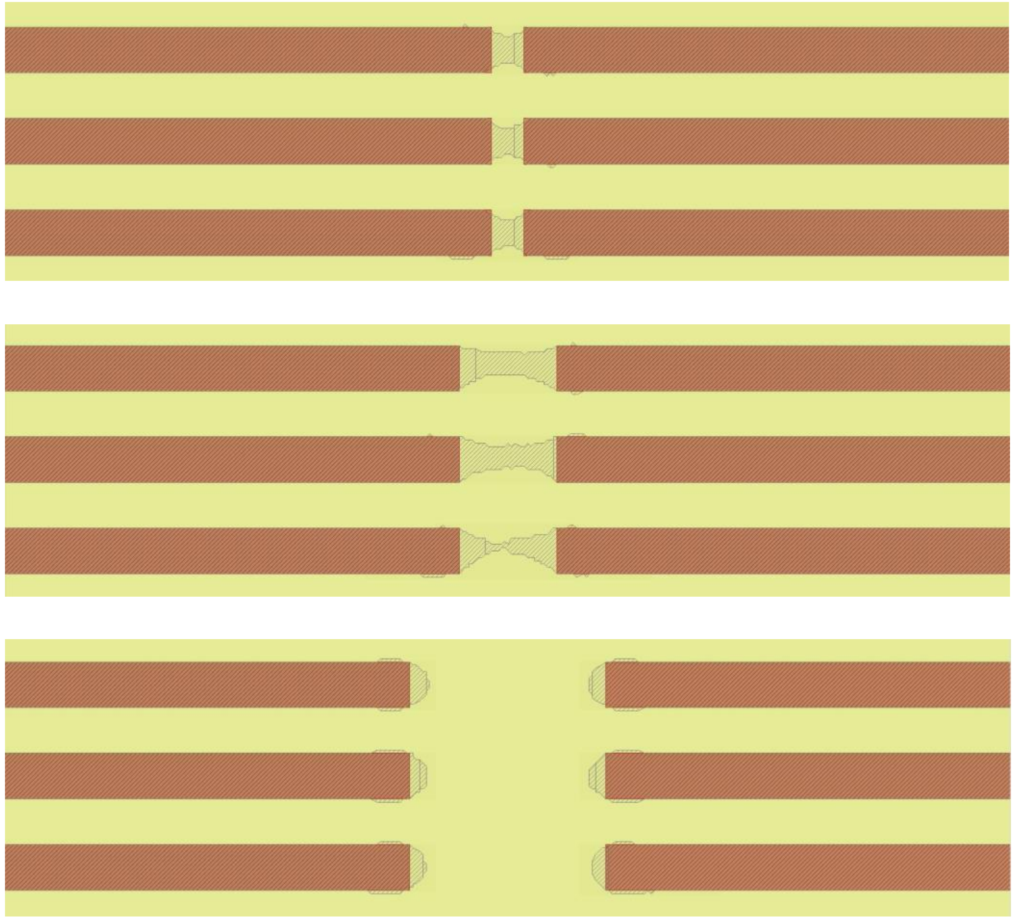
Botton and Top DSA contour evolution with array tip to tip gaps

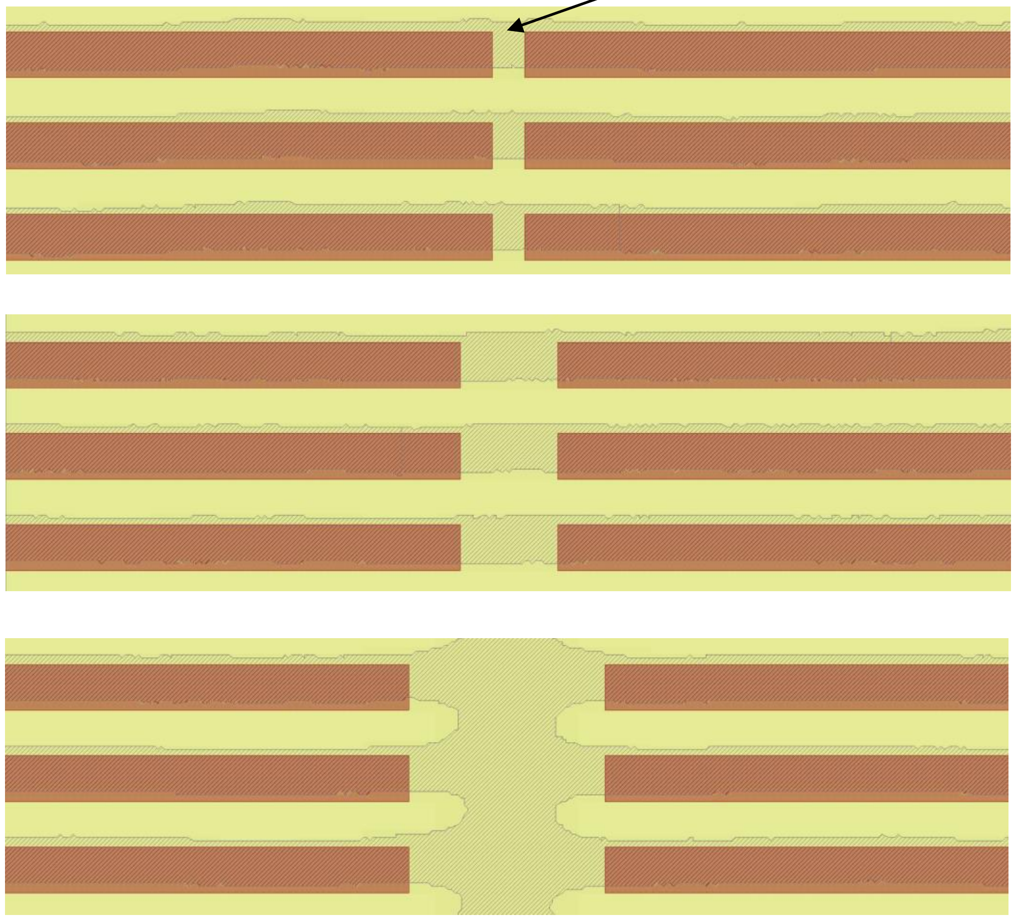


Red: guiding pattern
Grey: DSA pattern
Yellow: Neutral brush

Bottom DSA Contour



Top DSA Contour



Tip to tip Separation

10 nm

30 nm

60 nm

Pitch 28nm, CD = 14nm

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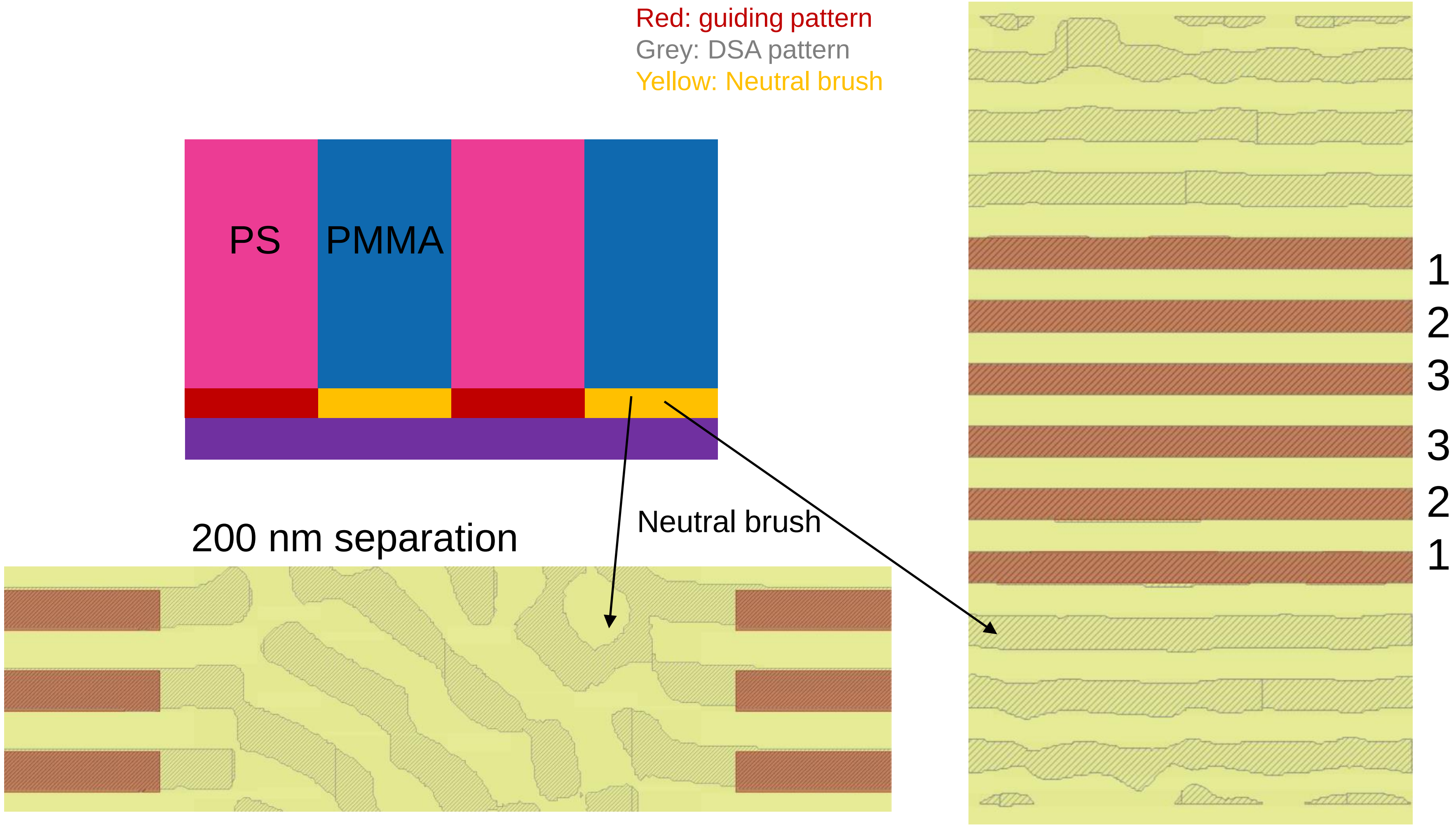
Investigation of Edge of the Array in both directions



Pitch 28nm, CD = 14nm

Lines #	LER (3σ nm)
1	1.35
2	0.69
3	0.03

- Line end LCDU are ok near the array termination, and finger print grows in between
- Line-space array, outer lines have larger LER compared with inner lines

Summary

- Demonstrated a rigorous simulation engine for DSA chemo-epitaxy patterning processes, to predict the post-process patterns for line space and hexagonal hole layouts.
- EUV rectification and DUV pitch-split cases are simulated for both L/S and contact holes.
- Simulation with varying guiding pattern CD shows a stable process window for different DSA flows.
- Terminated array simulation also provides information in the context of design rules.

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