Multiple Pitch Transmission and Phase Analysis of Six Types of Strong Phase-Shifting Masks

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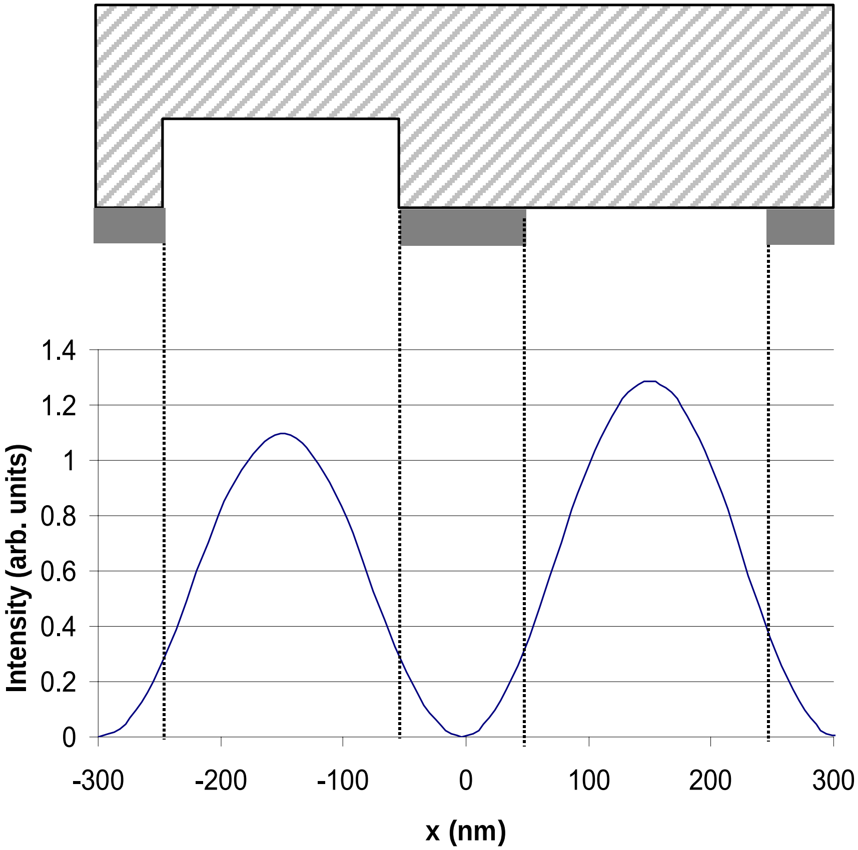
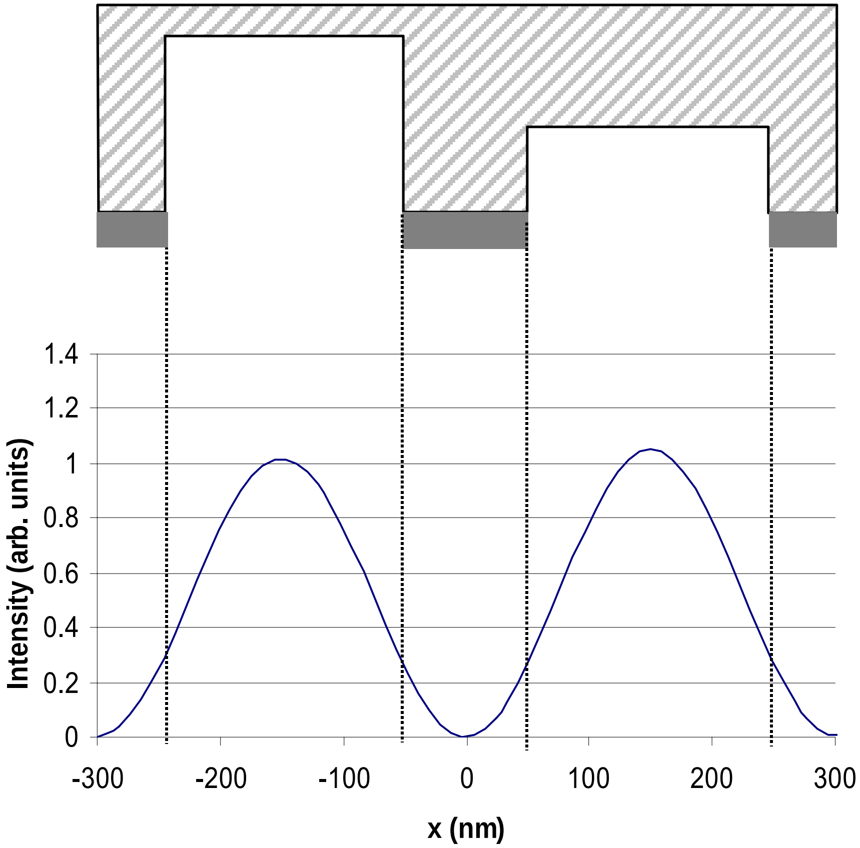
PSM Topography and Dual Trenches

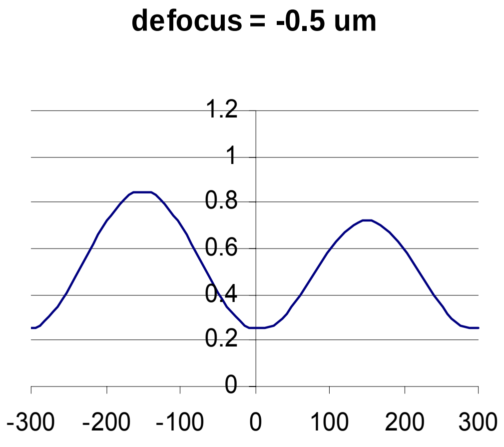
- A perfectly manufactured phase-shifting mask has an intensity imbalance between the shifted and unshifted intensity peaks.
- Adding a dual trench corresponding to a global phase shift of π radians can equalize the peaks.

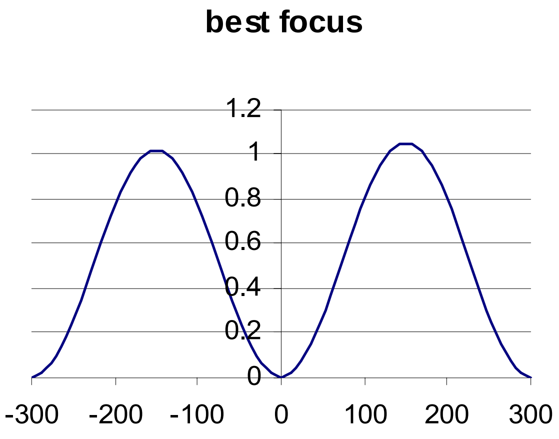


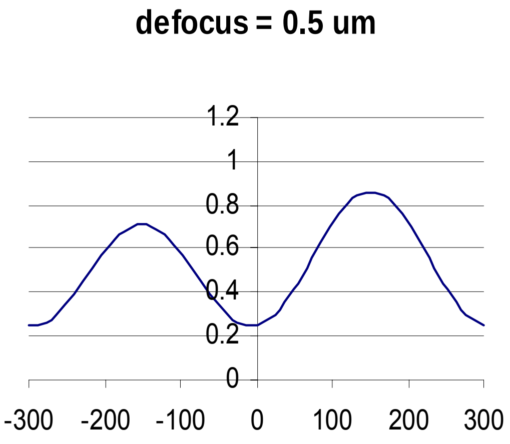


Phase Error

- More important, however, is the behavior of the shifted and unshifted peaks through focus.
- Note that the dual trench has shifted the intensity peaks apart. The peak equalization is therefore stymied out of focus.
- This means $\Delta\phi = 2\pi t(n-1)/\lambda$ is an insufficient model.



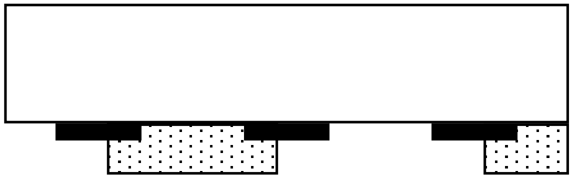




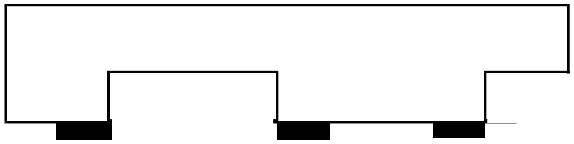
J. S. Petersen, et.al., SPIE Vol. 3564, p. 288 (1998)

Variations on the Theme

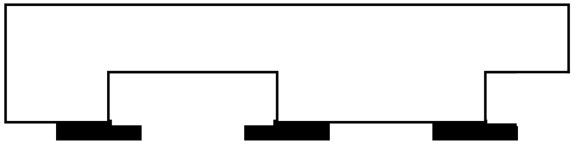
Additive



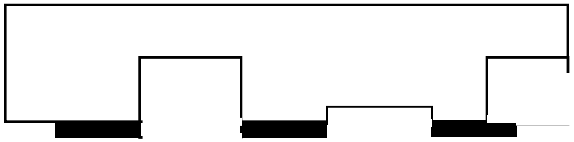
Selective Biasing



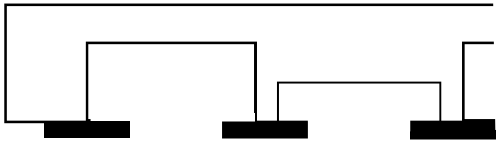
Undercut



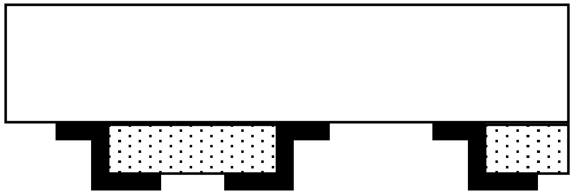
Dual Trench



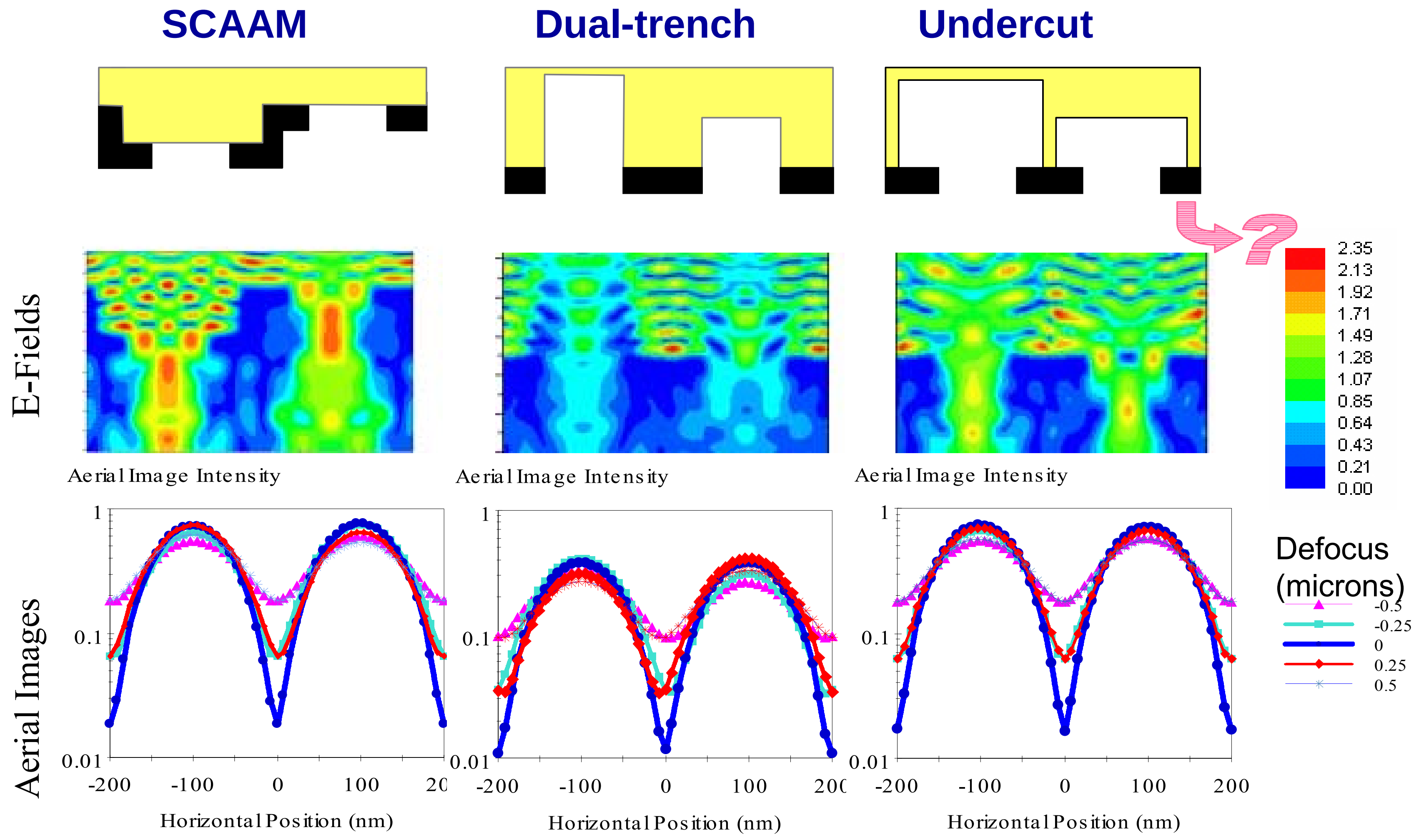
Dual Trench w/ Undercut



Side Chrome



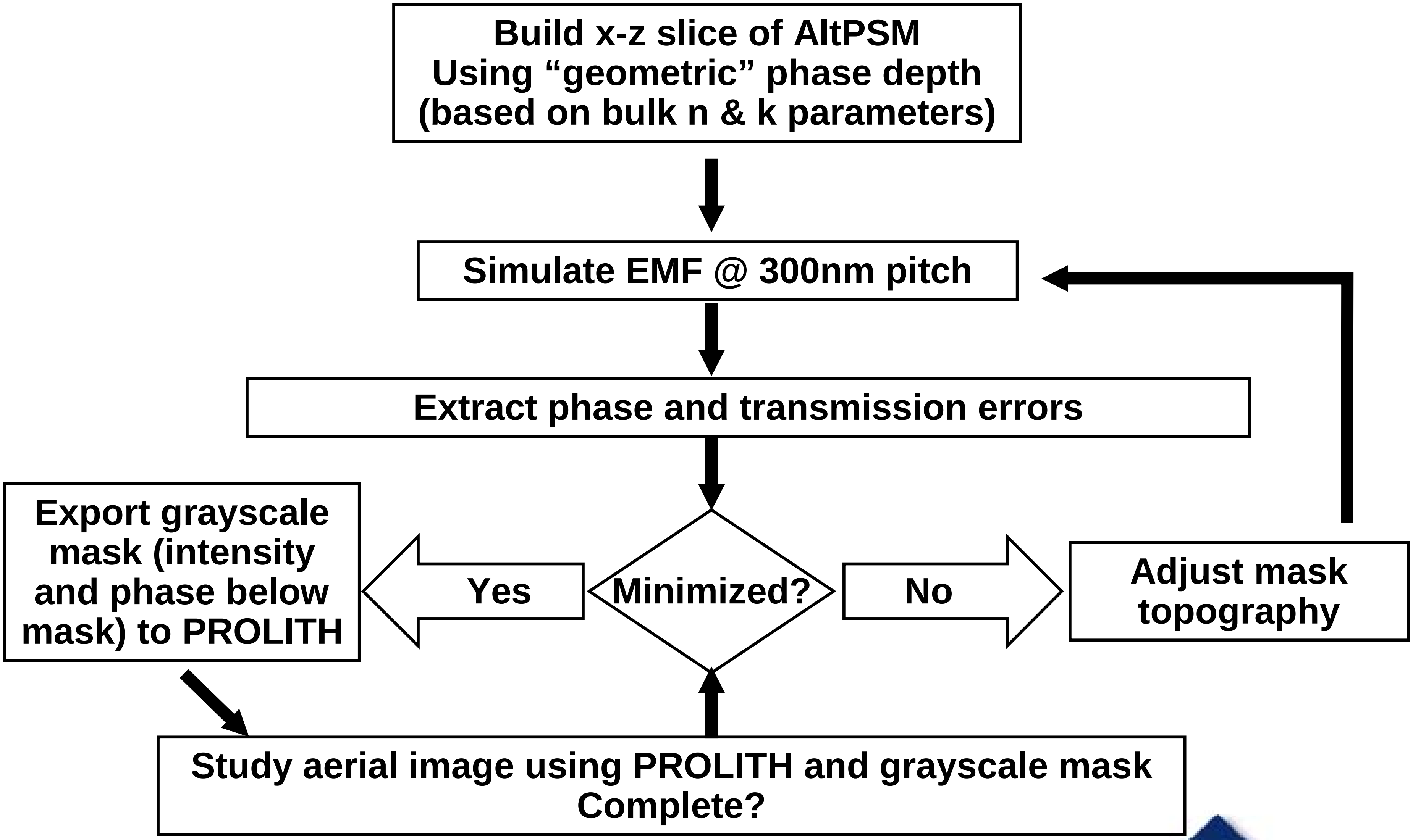
Imaging Comparison: Uncompensated SCAA vs. 2 Common Corrections



100 nm L/S pattern imaged at 248 nm with NA=0.744, $\sigma=0.2$, $k_1=0.3$.

ProMAX/2D & PROLITH/2

Alternating PSM Topography Design



Build x-z slice of AltPSM
Using "geometric" phase depth
(based on bulk n & k parameters)

Simulate EMF @ 300nm pitch

Extract phase and transmission errors

Minimized?

Yes

No

Export grayscale mask (intensity and phase below mask) to PROLITH

Adjust mask topography

Study aerial image using PROLITH and grayscale mask
Complete?

EMF Simulator Z-step Choice

- Simulator ‘accuracy’ = ƒ(grid size)
  - Test: Standing wave size in homogeneous index = 1,0 slab
  - Results:
    - ProMAX - errors reduce with finer grid to at least 500 steps/λ
    - TEMPESTp – errors reduce to limit of 73 steps/ λ (3.4nm @248nm)
    - But step size limit does NOT predict simulator accuracy
    - Convergence criteria differ, thus error magnitudes must be evaluated with user’s topographies on each simulator
- Phase-shift error due to grid quantization
  - Round all mask file coordinates to intended step sizes
  - Evaluate (actual – desired) phase-shift
  - Choose z-step trading off phase error (0-0.5deg) vs. run-time and simulator accuracy

Phase – Transmission Error Calculators

Analyze diffraction orders

- ProMAX: built-in analysis based on Ferguson[1] method
  - Implemented by C. Mack and modified to handle other than 1:1 duty
- TEMPESTp: Export orders and apply Peng[2] equations
  - Assumes equal line/space. For masks with unequal line/space, the Peng approach was used to extract phase but not transmission.

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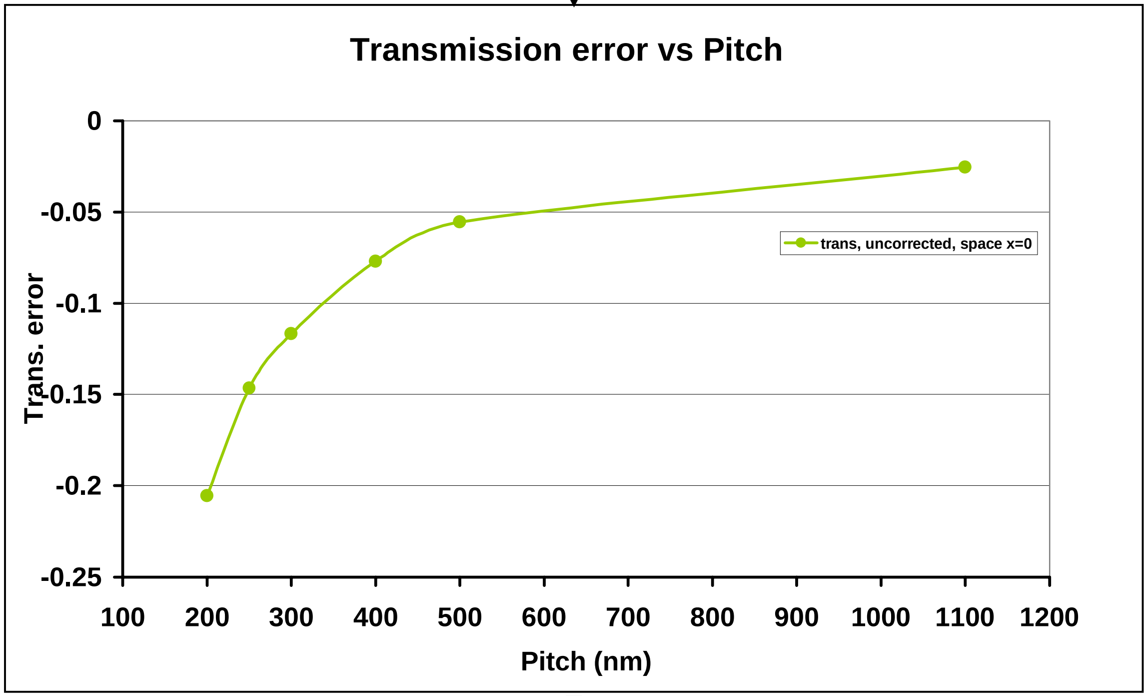
[1] R.A. Fergusen, A.K. Wong, T.A. Brunner, and L.W. Leibmann, "Pattern-Dependant Correction of Mask Topography Effects for Alternating Phase-Shifting Masks", Proc. SPIE 2440, 349-360 (1995)

[2] Peng, Song, "Through-Focus Image Balancing of Alternating Phase Shifting Masks", Proc. SPIE vol. 3873, p.328-336

Procedure, cont.

Optimize topography corrections @ 300nm pitch for phase and transmission

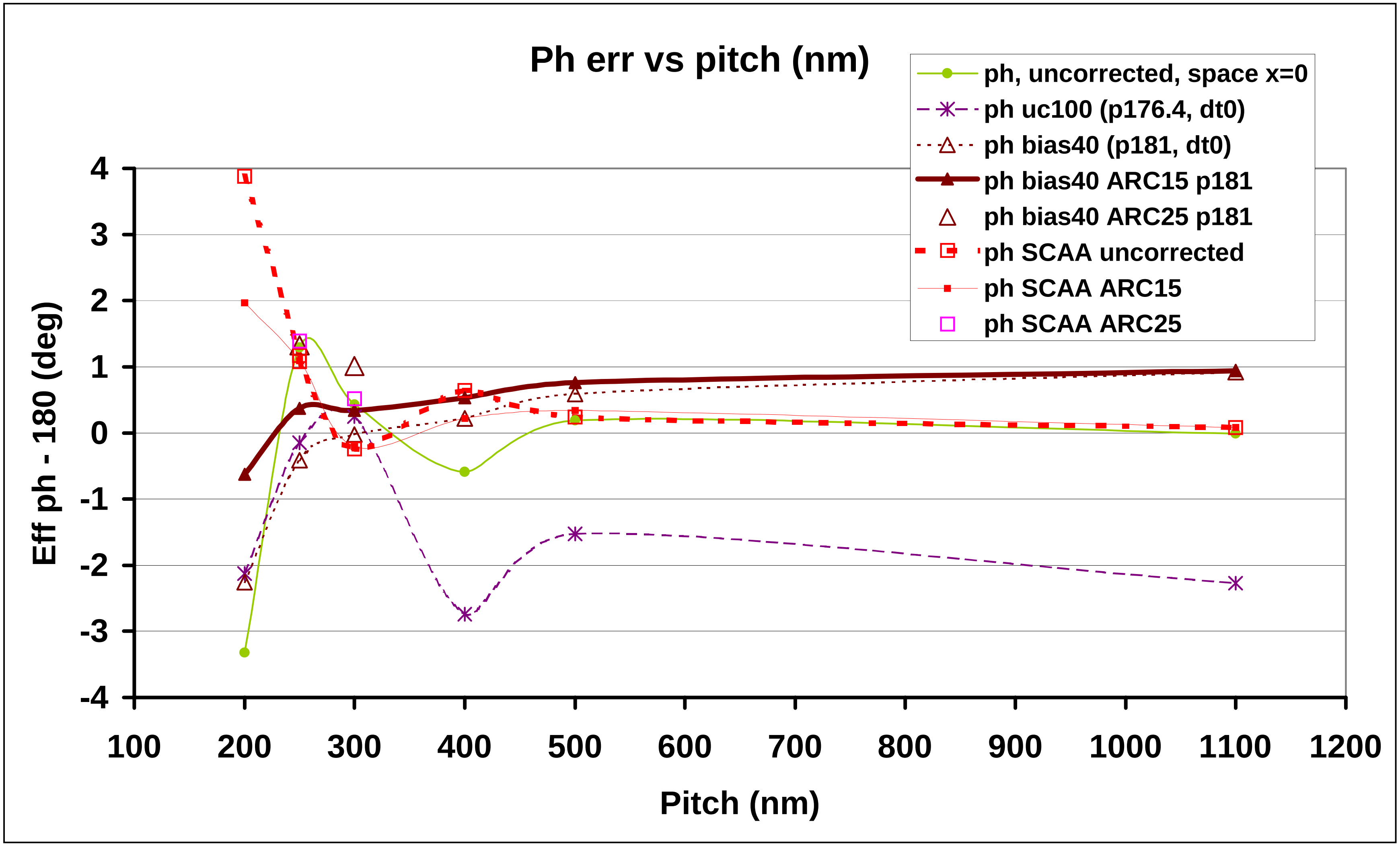
Apply these corrections across pitch



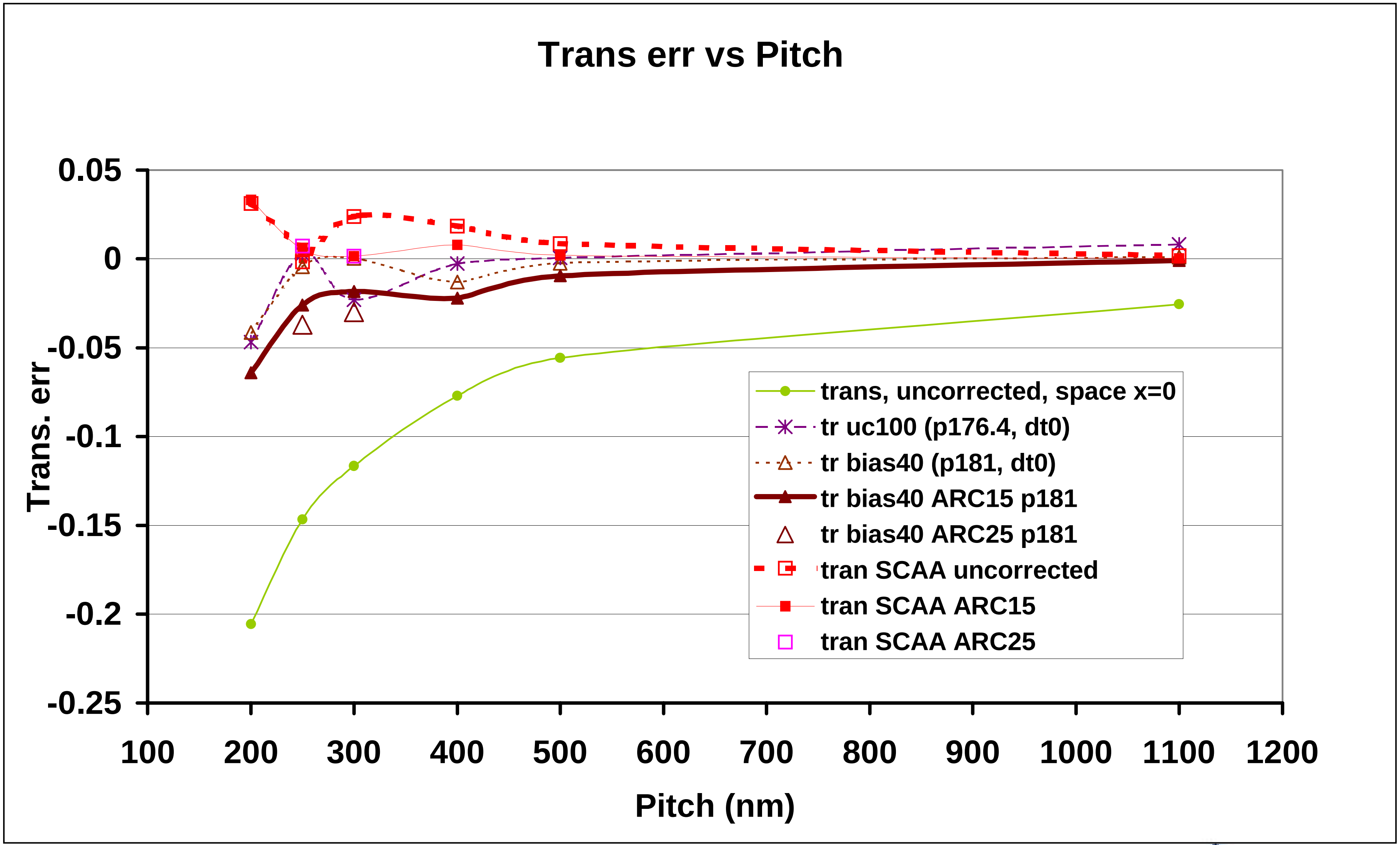
Uncorrected (“geometric”) mask, 248nm 100nm line

Study printability (aerial image, F/E, etc.)

Phase Errors Across Pitch



Transmission Errors Across Pitch



Phase and Transmission Results

	Pitch 200nm		Pitch 250nm		Pitch 300nm		Pitch 400nm		Pitch 500nm		Pitch 1100nm	
Correction Type	Ph	Tr	Ph	Tr	Ph	Tr	Ph	Tr	Ph	Tr	Ph	Tr
SCAA (1)	2.0	0.033	1.1	0.005	-0.2	0.002	0.2	0.008	0.3	0.002	0.1	0.000
Asym. Bias (2)	-2.3	-0.041	-0.4	-0.004	0.0	0.000	0.2	-0.013	0.6	-0.002	0.9	0.001
SCAA (uncorrected)	3.9	0.031	1.2	0.005	-0.2	0.024	0.6	0.018	0.2	0.009	0.1	0.002
AsymBias (4)	-0.6	-0.064	0.4	-0.026	0.3	-0.018	0.5	-0.022	0.8	-0.010	0.9	-0.001
Additive (uncorrected)	-3.8	0.120	-1.7	0.031	-1.4	0.001	-0.2	-0.002	-0.3	0.004	0.1	0.001
Additive (6)	-3.6	0.099	-0.2	0.029	0.2	0.001	1.7	0.002	1.4	0.006	1.9	0.005
Undercut (7)	-2.1	-0.047	-0.2	0.003	0.3	-0.023	-2.7	-0.003	-1.5	0.001	-2.3	0.008
Dual-trench + Undercut (8)	-8.8	-0.008	-1.2	-0.060	1.2	-0.007	3.0	-0.024	4.3	-0.015	5.8	-0.007
Phase only (9)	-4.1	-0.195	0.7	-0.136	-0.3	-0.108	-1.2	-0.068	-0.4	-0.046	-0.5	-0.017
None	-3.3	-0.205	1.3	-0.147	0.4	-0.117	-0.6	-0.077	0.2	-0.056	0.0	-0.025
Dual-trench (11)	12.4	0.037	0.3	-0.007	-2.2	0.025	-5.2	0.000	-5.6	0.005	-7.9	0.000

KEY	Phase: |Effective phase - 180deg|	Transmission: |(shiftedspace tran - unshifted space tran)|
🟩 GOOD	0-.5	0-.025
🟦 OK	0.5-1.5	.025-.05
🟥 POOR	>1.5	>.05

-Conditions for each mask type fixed by optimization at 100/200nm line/space

-100nm line masks ranked by overall performance across pitch using normalized power in central diffraction orders as figure of merit.

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Notes on Mask EMF Results

- Mask Conditions after optimization for 100-200 line-space, λ=248nm

1: SCAA, 15nm ARC
2: Asym Bias, 181deg phase, 40nm bias
3: SCAA, no correction
4: Asym Bias, 15nm ARC, 40nm bias
5: Additive, uncorrected
6: Additive, 182 deg phase
7: Undercut (UC), 100nm UC, 176.4deg phase
8: Dual-trench + Undercut, 225nm+20nm 173.8deg phase
9: Phase only, 179.7deg phase
10: Geometric (no correction)
11: Dual-trench, 270nm DT 172.5deg phase

- Ranking by diffraction order power:

	Across Pitch Range		
	Phase	**Trans**	**power sum***
SCAA (1)	2.2	0.033	0.00002
Asym. Bias (2)	3.2	0.043	0.00004
SCAA (uncorrected)	4.1	0.033	0.00006
AsymBias (4)	1.6	0.063	0.00007
Additive (uncorrected)	3.9	0.122	0.00014
Additive (6)	5.4	0.098	0.00017
Undercut (7)	3.0	0.055	0.00017
Dual-trench + Undercut (8)	14.6	0.054	0.00051
Phase only (9)	4.8	0.177	0.00076
None ("geometric")	4.6	0.180	0.00089
Dual-trench (11)	20.3	0.043	0.00123

$$\text{*Power sum} = \sum_{\textbf{pitch 1}}^{\textbf{pitch n}} (P0 / 2P1)_n$$

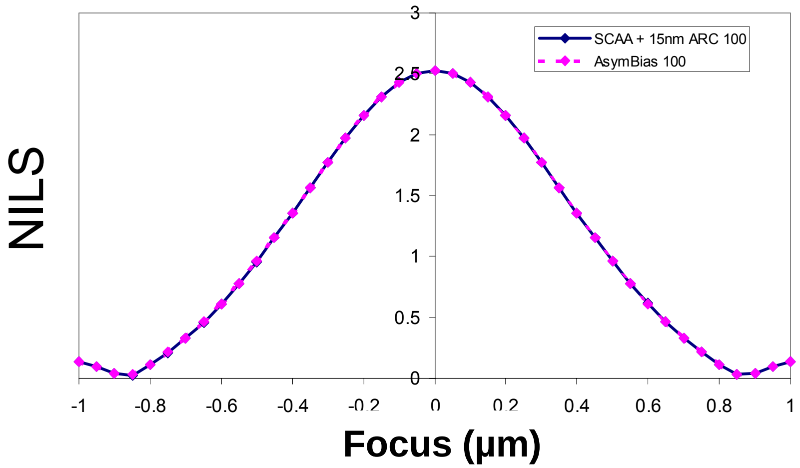
P0 = power in central diffraction order
P1 = power in 1st diffraction order
(2P1 because of two first orders)

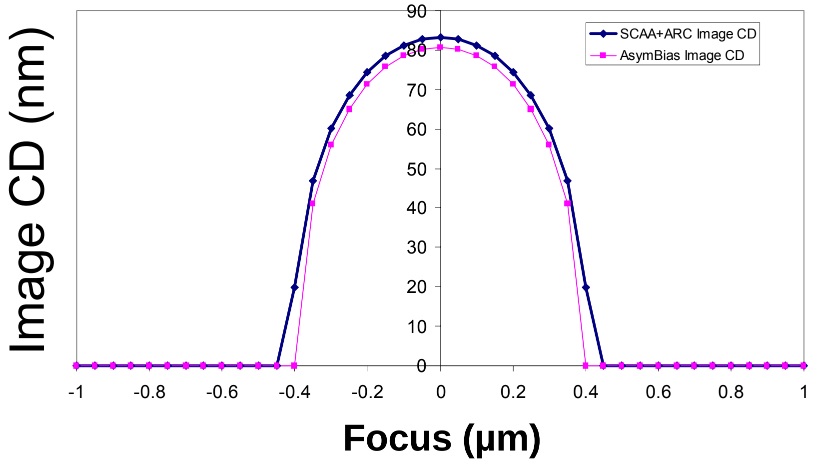
AltPSM MEEF Comparison

- Masks: SCAA (15nm CrO_3 ARC) and Asymmetric Bias (+40nm bias, 181deg phase). Two best masks chosen from earlier table ranking across pitch performance.
- Input variation: ±40nm mask CD variation for the two best altPSM masks
- Simulation outline:
  - Construct ProMAX masks that have wafer line dimensions of 90nm, 100nm and 110nm with 300nm pitch
  - Run EMF simulations
  - Export “grayscale” (intensity and phase slice) masks to PROLITH 7.0 and simulate focus-exposure. Monitor CD, sidewall angle, resist loss and image placement.
  - Port FE matrix results to ProDATA and analyze process window using line CD and image placement as responses.
    - CD limits 90 to 110nm
    - Image placement |–5nm to 5nm|

NILS Comparison of SCAA with 15nm ARC and Asymmetric Bias

- NILS through focus for 300nm pitch both mask types are identical.
- Image CD for SCAA is least sensitive to focus.





Simulation Conditions
PROLITH 7.0
0.63 NA, 248nm 0.30 sigma

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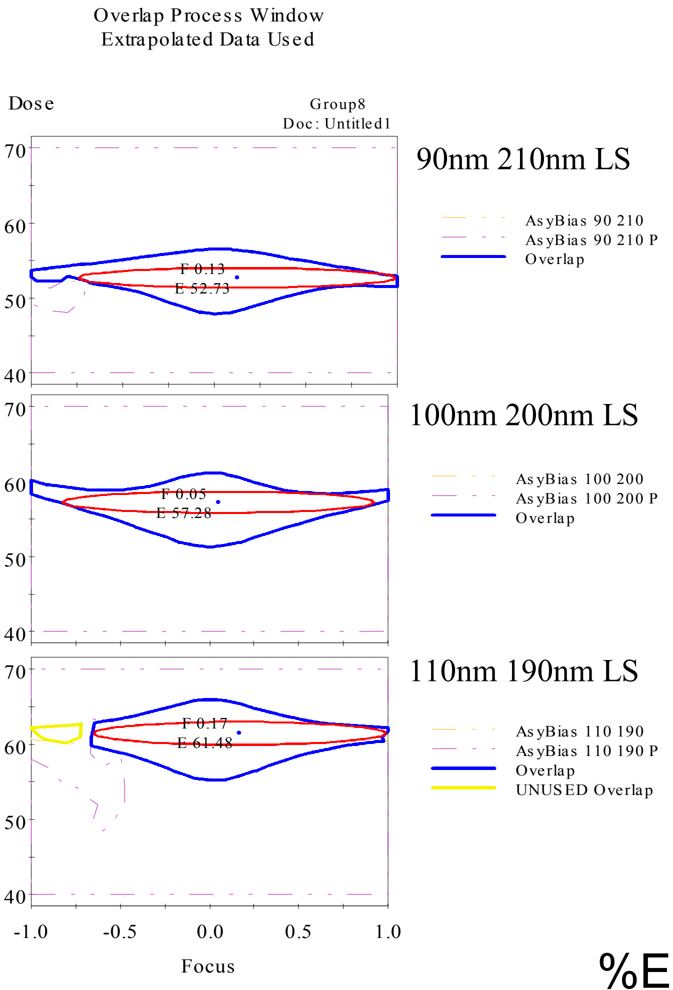
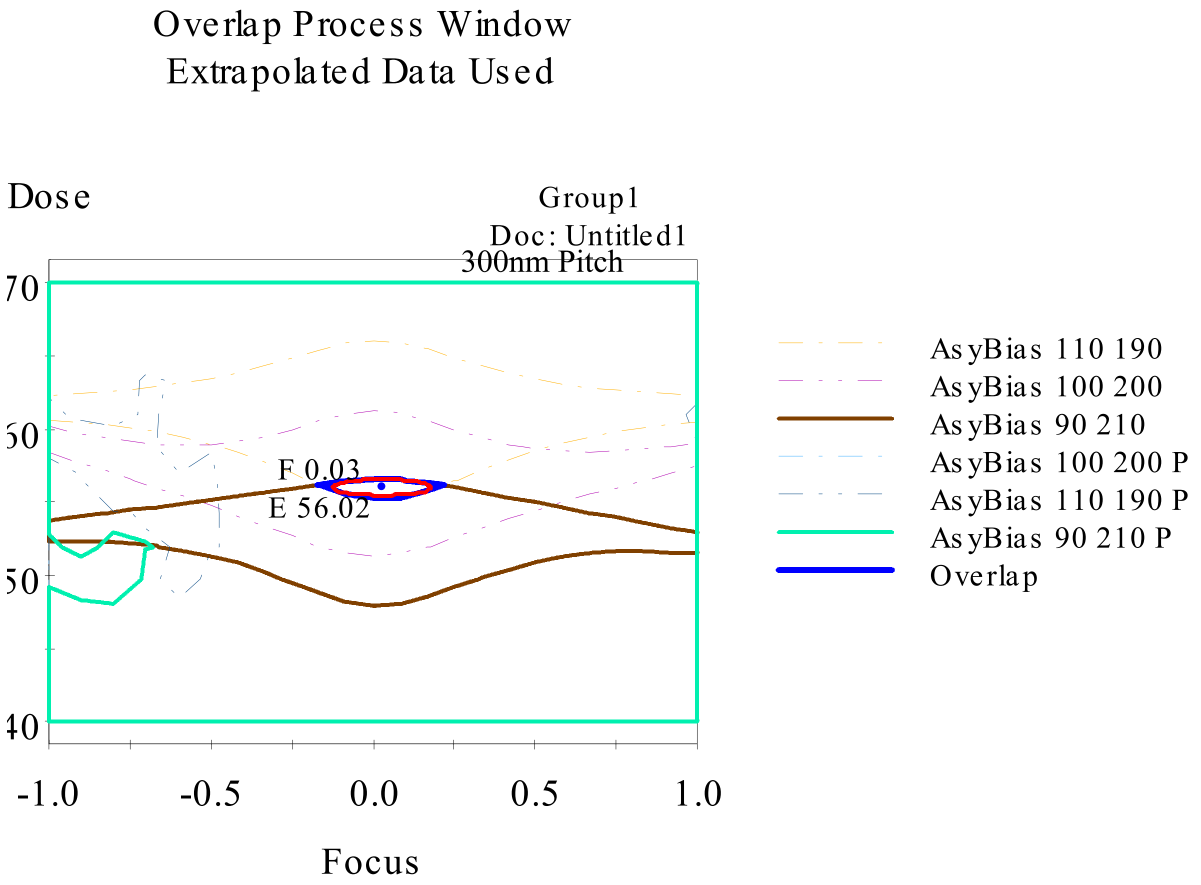
Asymmetric Bias Process Window MEEF for 300nm Pitch



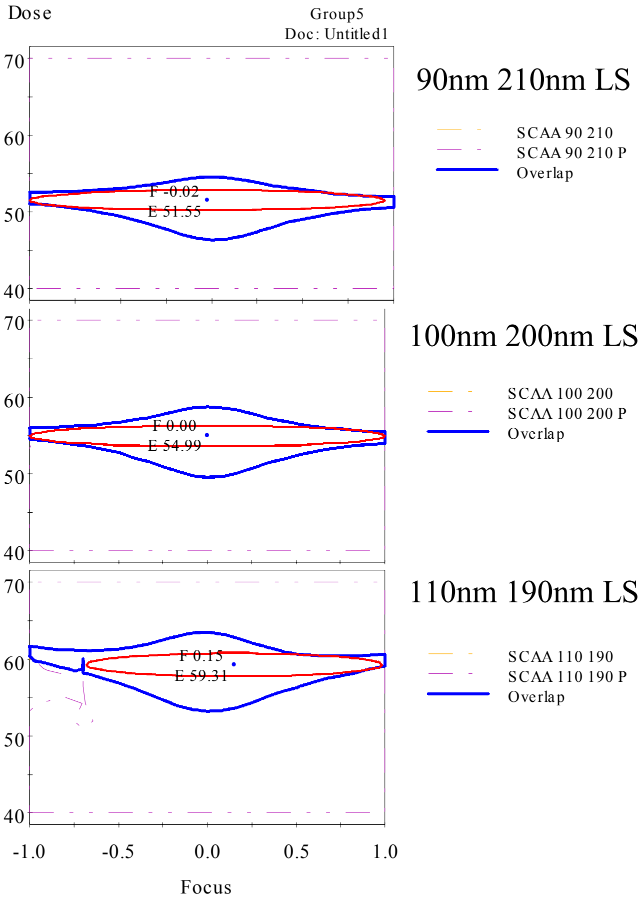


%EL=5% Lower Limit
P= Image Placement Spec of |-5nm to 5nm|

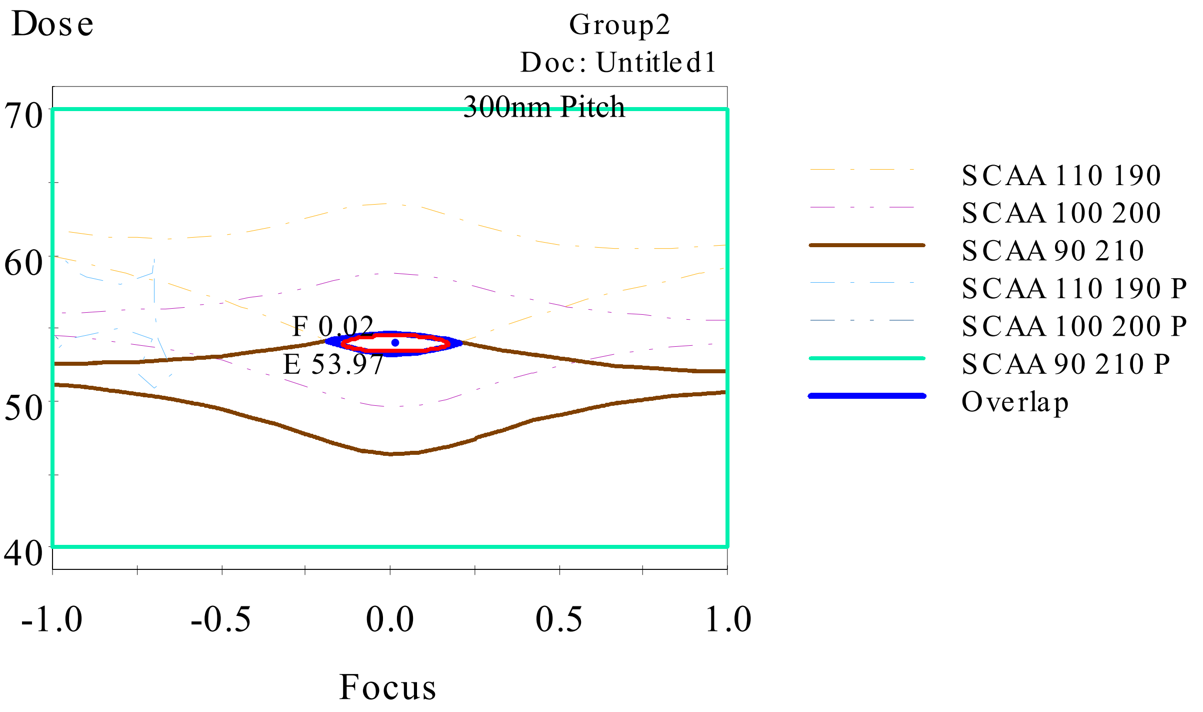
Simulation Conditions
PROLITH 7.0
0.63 NA, 248nm 0.30 sigma
304nm UV113 on 20nm CD11+62.5nm AR-5
Klarity ProData PW analysis

SCAA Process Window MEEF for 300nm Pitch

Overlap Process Window
Extrapolated Data Used



Overlap Process Window
Extrapolated Data Used



Simulation Conditions
PROLITH 7.0
0.63 NA, 248nm 0.30 sigma
304nm UV113 on 20nm CD11+62.5nm AR-5
Klarity ProData PW analysis

%EL=5% Lower Limit
P= Image Placement Spec of |-5nm to 5nm|

MEEF Comparison Summary

- For the two best altPSM mask types, SCAA with 15nm Top ARC and 40nm Asymmetric Bias:
  - Similar MEEF of 0.9
  - Common process window of 0.3µm with 2% Exposure Latitude (%EL) for ±40nm mask CD variation.
  - Production process requires less than ±40nm mask CD variation.
- For SCAA performance within a single line:
  - 90nm and 100nm lines have 12 to 14% more DoF than AsymBias
  - 110nm lines have 2.4% more DoF than AsymBias
- 110nm line performance is limited by image placement for both masks, but AsymBias is the worst.

Type	Line Size 300nm Pitch	$E_{S=100nm}$	CD @ $E_{S=100nm}$	MEEF	$E_{PWCenter}$	DoF	w/X% EL	Phase Error	Tran Error
SCAA+15nm ARC	90.0		92.0		51.6	1.95	5	+0.25	-0.005
SCAA+15nm ARC	100.0	54.2	98.0	0.88	55.0	2	5	-0.21	0.002
SCAA+15nm ARC	110.0		109.0		59.3	1.67	5	-0.64	0.012
SCAA+15nm ARC	Common				55.0	0.3	2		
AsymBias	90.0		91.0		52.7	1.73	5	+0.21	-0.013
AsymBias	100.0	56.5	97.0	0.90	57.3	1.75	5	-0.02	0.000
AsymBias	110.0		109.0		61.5	1.63	5	+0.52	-0.005
AsymBias	Common				56.0	0.3	2		

Conclusion

- SCAA with 15nm ARC performed best across pitch regarding phase and transmission errors at the mask plane, followed closely by the asymmetric biased mask (with 40nm bias each side of shifted space and 181deg design phase shift)
- All mask types except SCAA required EMF simulation for topography optimization
- EMF mask optimization requires systematic simulator setup and grid quantization to bound designed-in errors from desired phase, and to optimize simulator accuracy
- NILS through focus @ 300nm pitch for best SCAA and biased mask types are identical, whereas Image CD through focus is better for SCAA
- For best SCAA and biased masks, each has similar MEEF of 0.9
  - Common process window of 0.3µm with 2% Exposure Latitude (2% due to large line change chosen, +/- 10nm at wafer, +/- 40nm at mask)
  - Even with small MEEF, both mask types require less than ±40nm mask CD variation for a production process
  - 110nm line performance is limited by image placement for both masks, but AsymBias is the worst

Acknowledgements

Chris Mack, FINLE Technologies, a division of KLA-Tencor, for ProMAX development and consulting

Tom Pistor, Panoramic Technologies for TEMPESTp