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Printing EUV Phase-shift Masks using the 0.3NA Berkeley Micro-exposure Tool

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Printing EUV Phase-Shift Masks using the 0.3NA Berkeley MET

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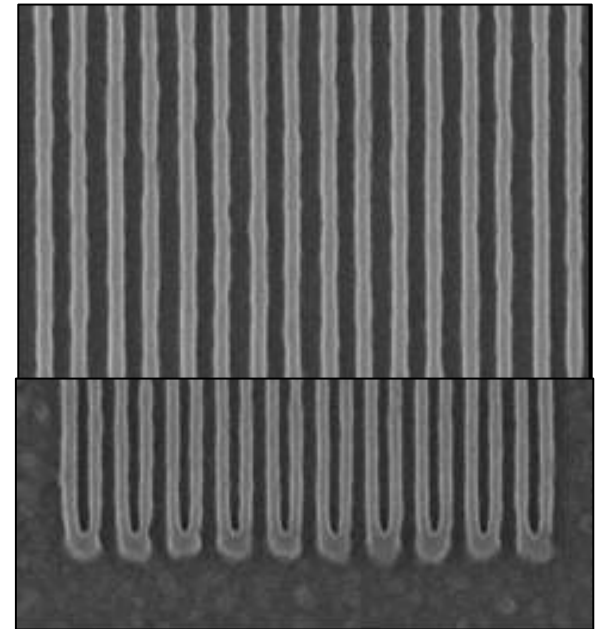
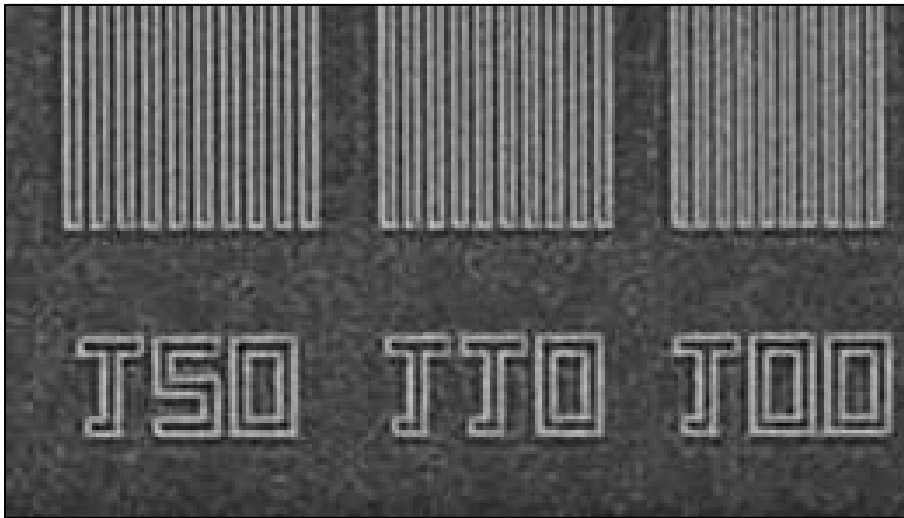
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CPL-like phase-shift masks for EUVL

- We have demonstrated the printing of EUV phase-shift masks based on direct etching of the multilayer reflector.
- This is illustrated by phase-edge printing in resist of etched features on the mask



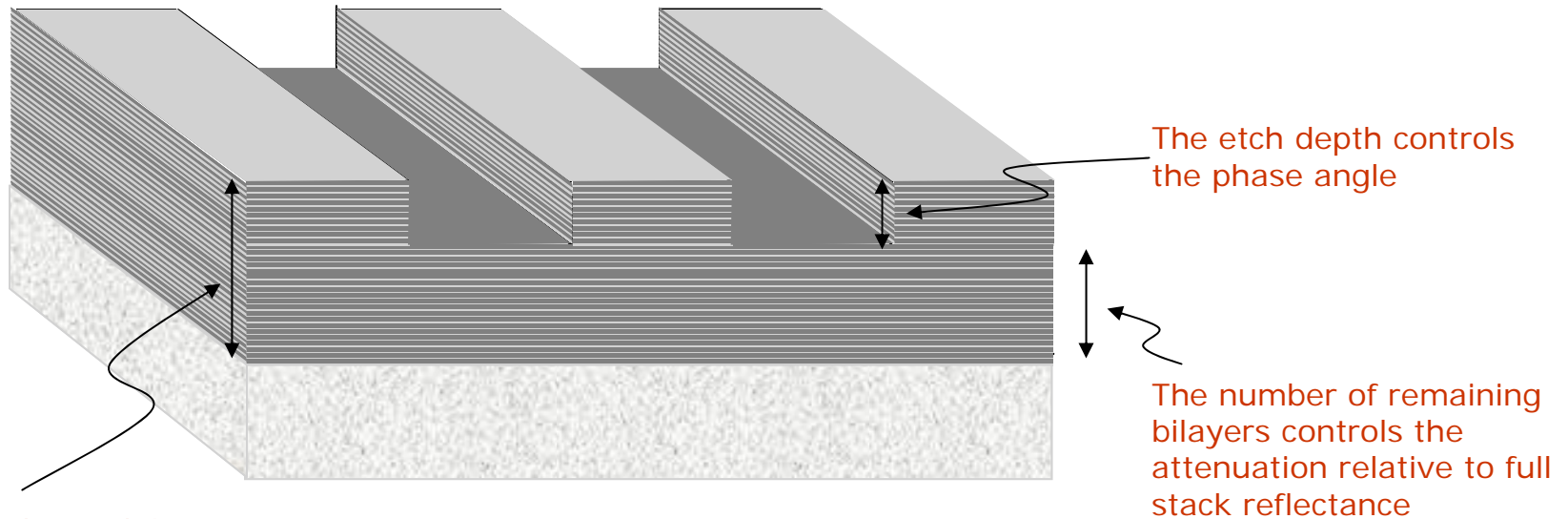
Phase-edge prints of
80nm lines

Outline of the presentation

- Concept and design of EUV phase-shift masks
- The fabrication of phase-shift masks
- First printing results and simulations
- Spectral response
- Early results from second mask
- Future work

EUV phase-shift mask concept

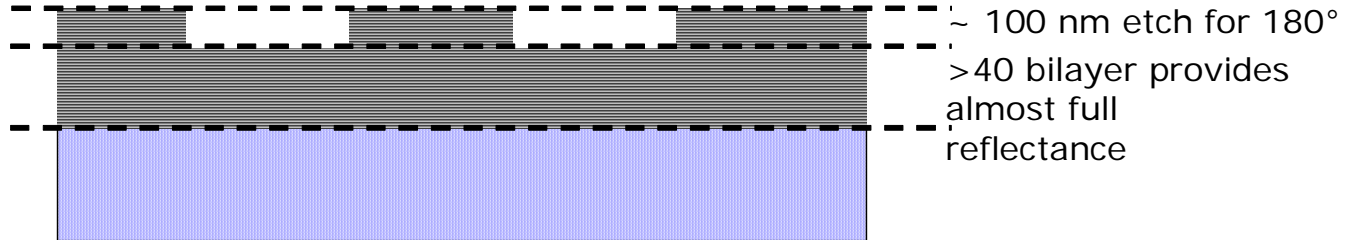
- The EUV PSM concept that we are evaluating is based on etched multilayer techniques
- EUV PSMs are needed for focus and aberration monitoring
- EUV PSMs can also provide high contrast aerial images at small CD for resist testing



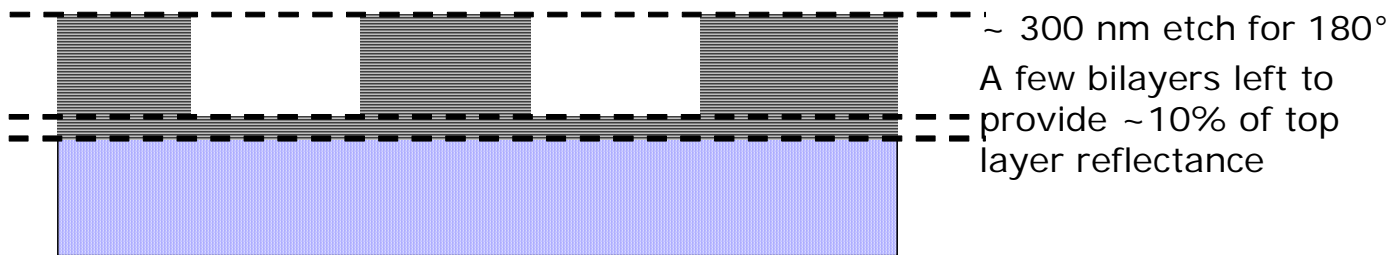
Any type of PSM can be fabricated this way: *CPL, att-PSM, alt-PSM*

Types of EUV Phase-shift masks

- CPL-like (PSM1 & PSM3)



- Att-PSM (PSM2)



- Alt-PSM (not yet fabricated)

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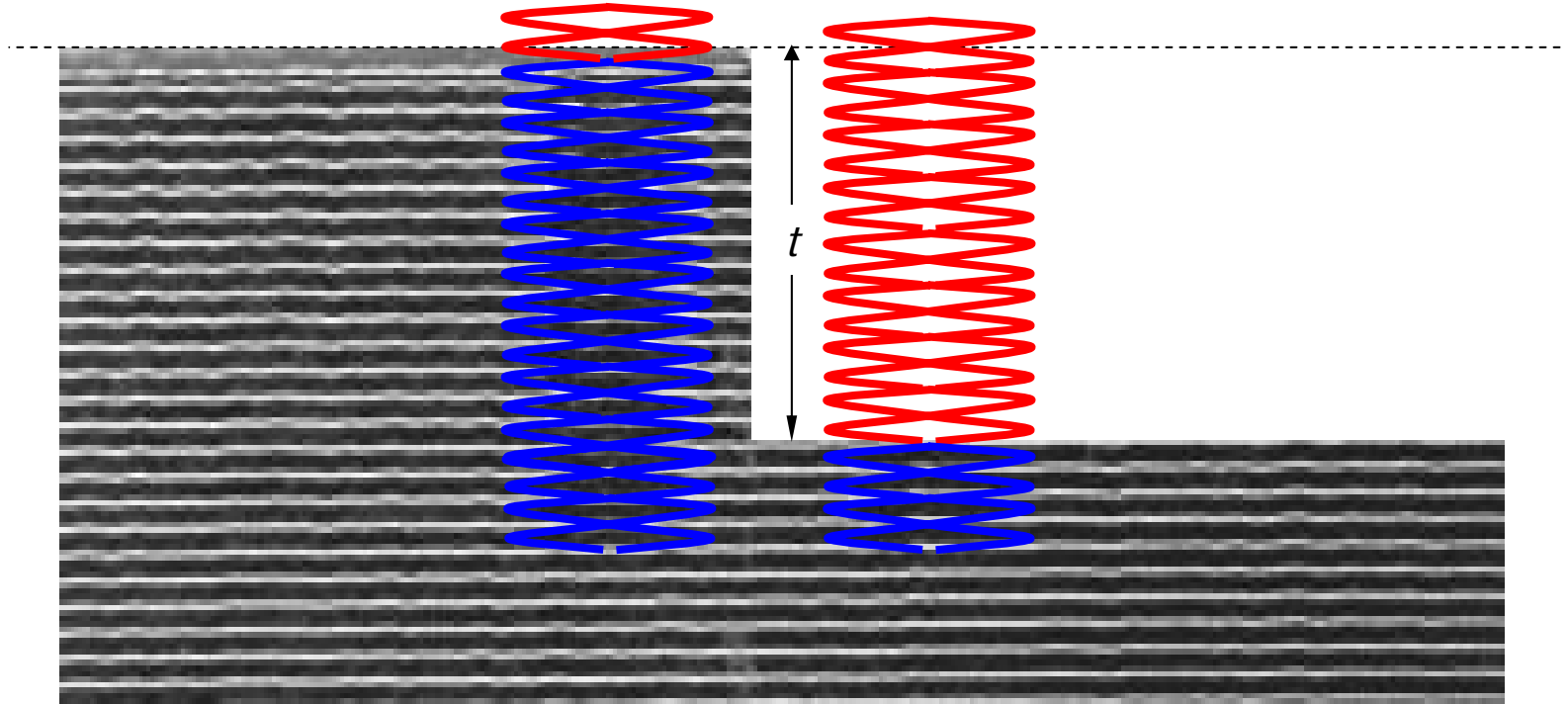
-- ~ 100 nm etch for 180°
-- Absorber or complete etch can provide desired contrast

EUV PSM design

- Index of refraction of multilayer is very close to that of vacuum

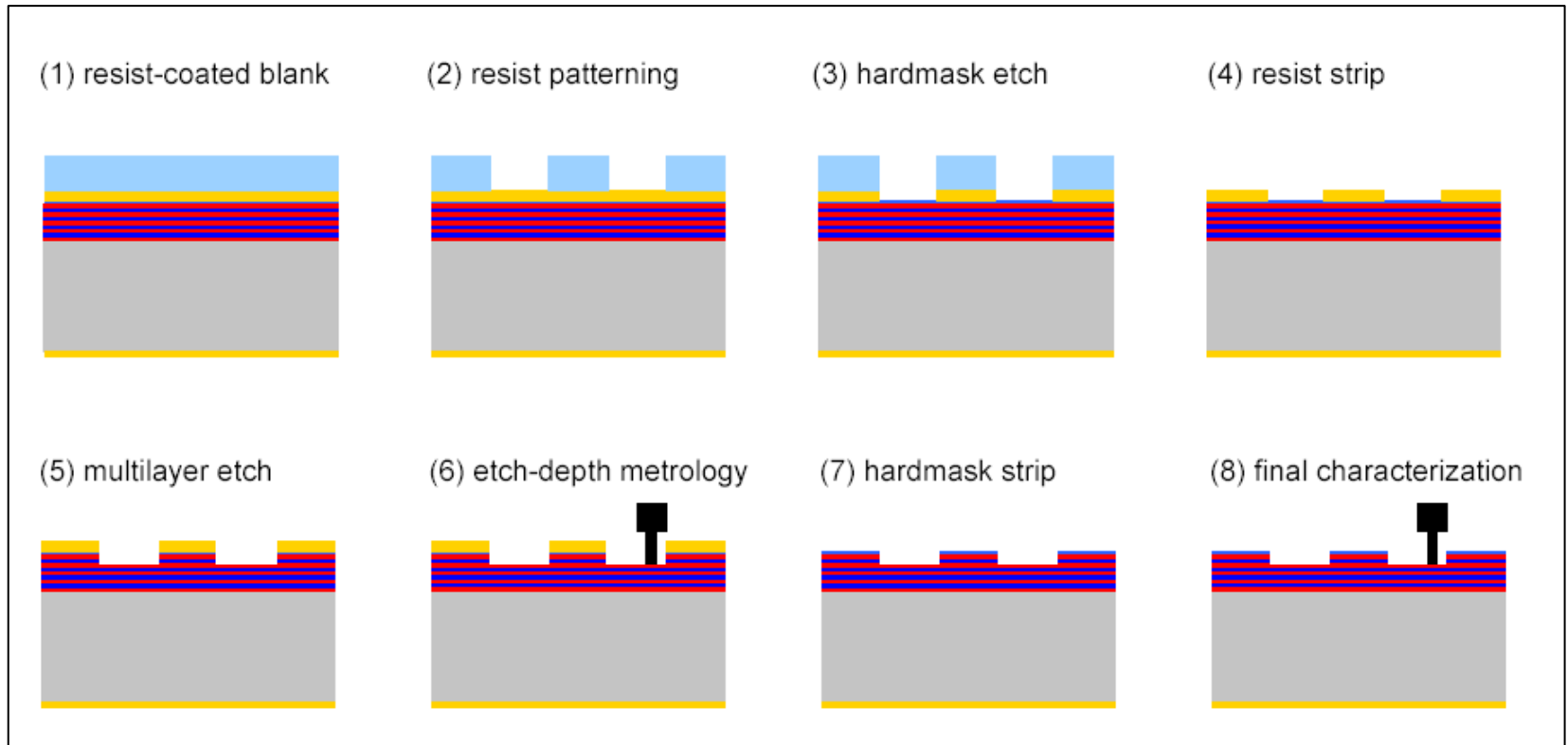
$$\frac{2\Delta n t}{\lambda \cos \theta} = \frac{\Delta \phi}{2\pi} \quad \text{with } \Delta n \sim 0.03 \longrightarrow \frac{t}{\Delta \phi} \sim 0.6 \text{ nm}/^\circ$$

- π phase shift corresponds to ~ 110 nm etch depth



The fabrication of EUV Phase-shift masks

- Description of process flow (AMTC/IMS-Chips)

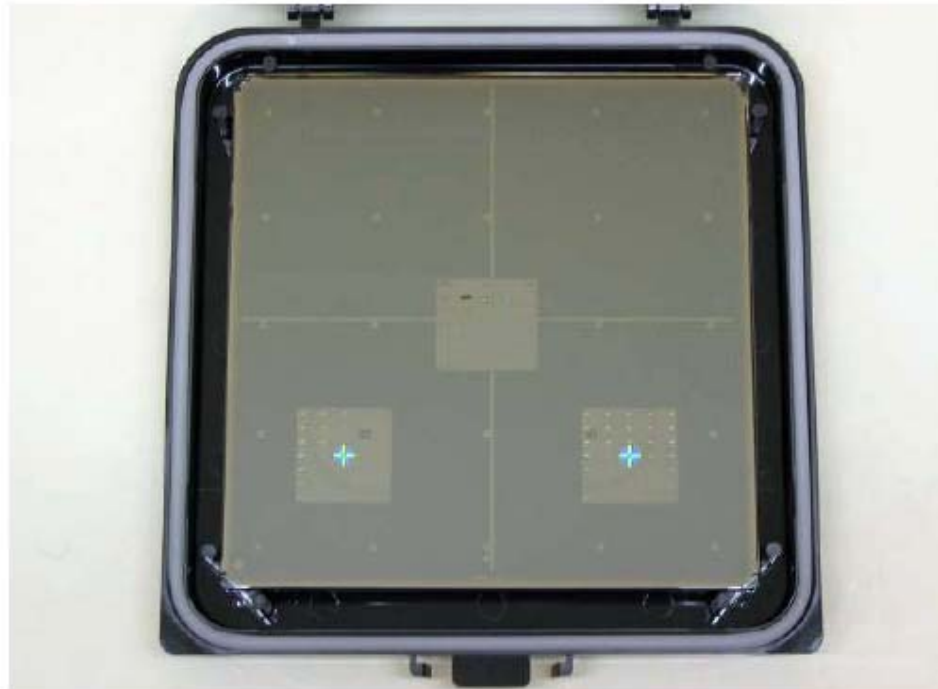


First etched-multilayer EUV PSM

PSM1 is a 'CPL-like' phase-shift mask

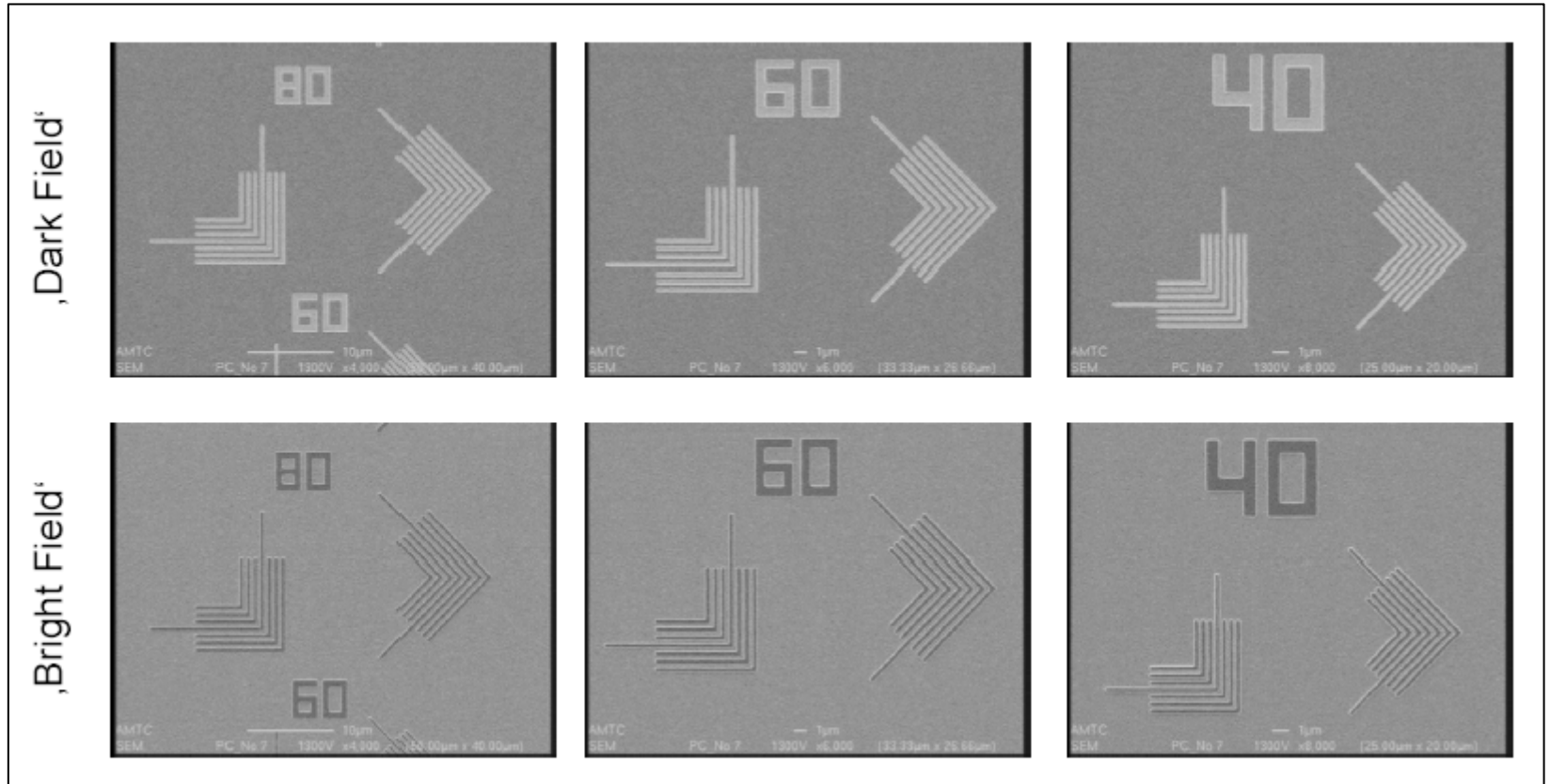
ADVANCED MASK  TECHNOLOGY CENTER

Final Mask (Post-hardmask Strip)



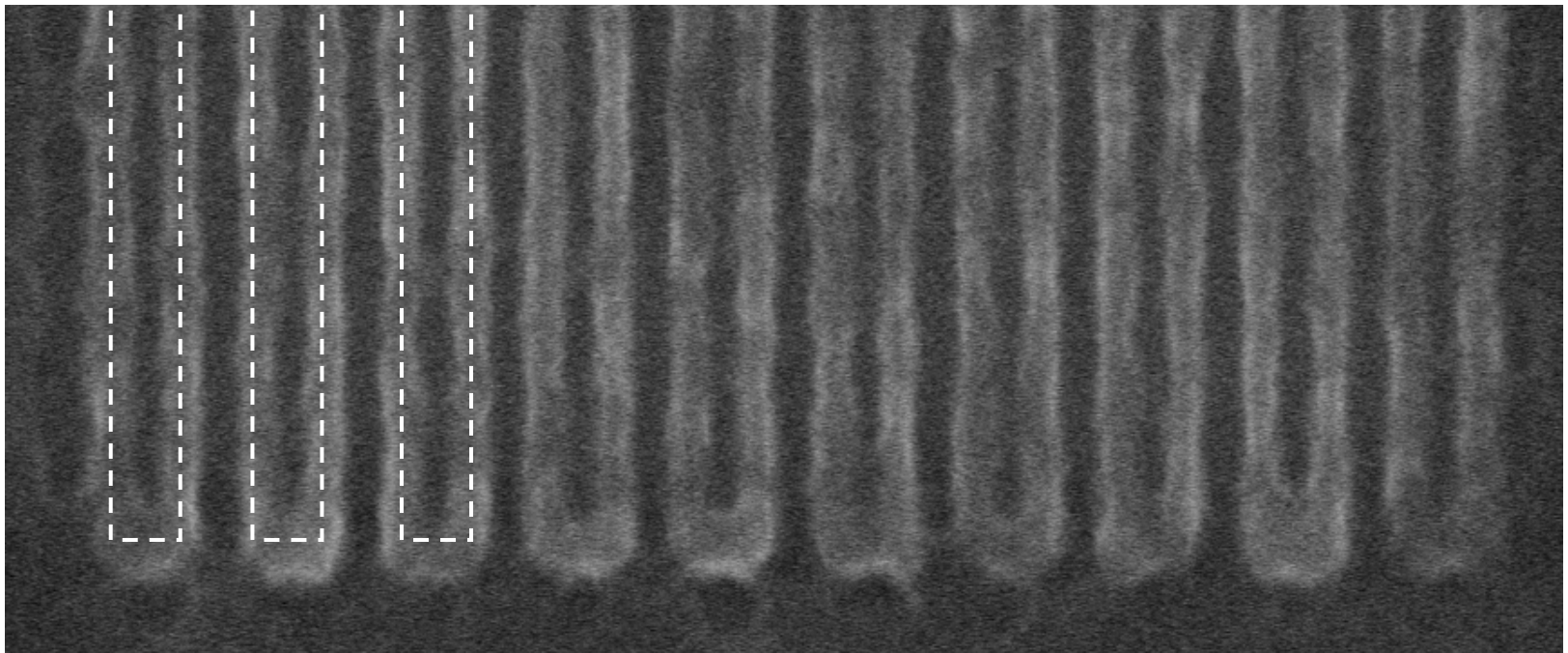
Sample features on PSM1 mask

- Etch depth of 81 nm with good uniformity across the central imaging area



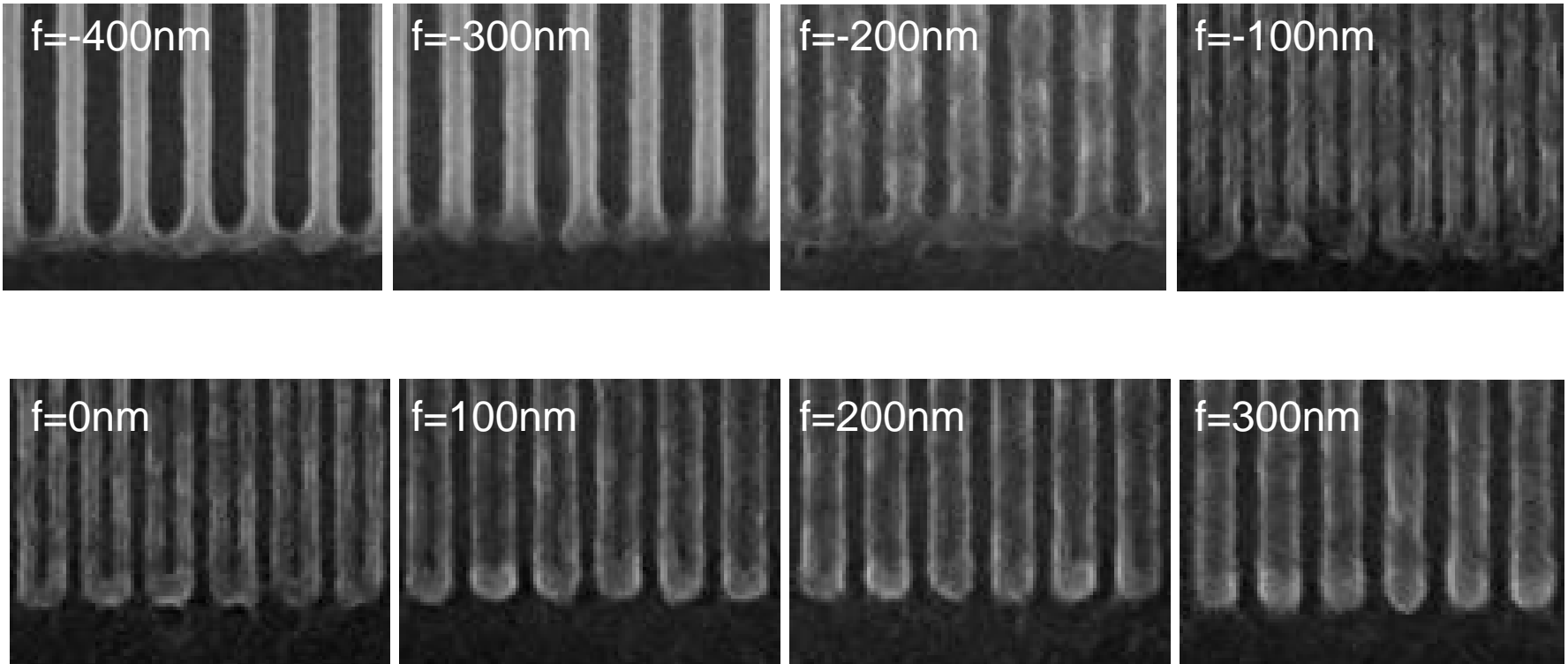
First print with mask PSM1

- Phase edges of this 'CPL' mask clearly print
- This is the first print recorded using an EUV phase-shifting mask patterned by partially etching the multilayer reflector film
 - $\lambda=13.5$ nm, monopole illumination, resist: MET 1K on BARC
 - Programmed 80-nm lines & spaces



Through focus behavior of PSM1 print

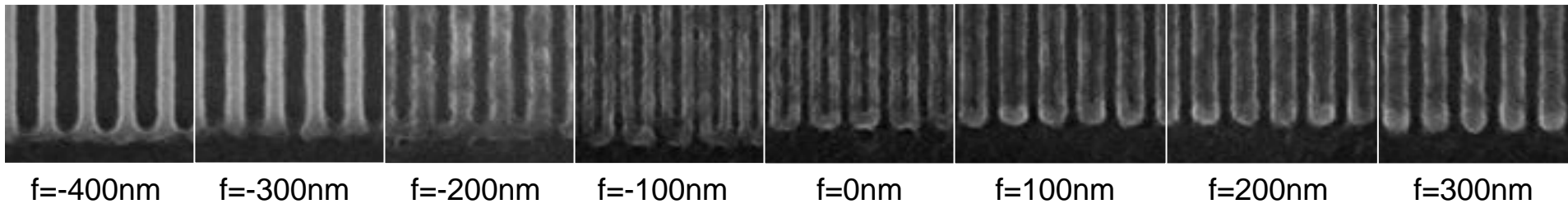
- Tone reversal observed (characteristic of phase objects)
 - 100 nm focus steps at constant dose



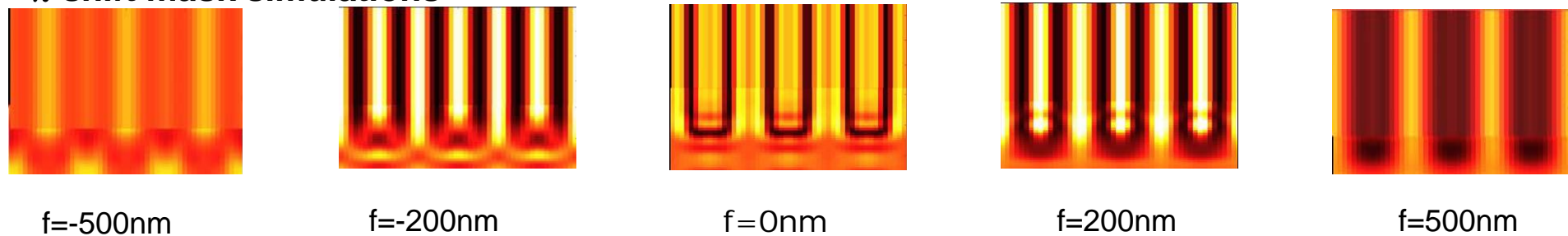
Comparing PSM1 results to simulations

- Fair qualitative agreement:
 - Trend showing frequency doubling and tone reversal through focus is reproduced in the simulations

PSM1 prints

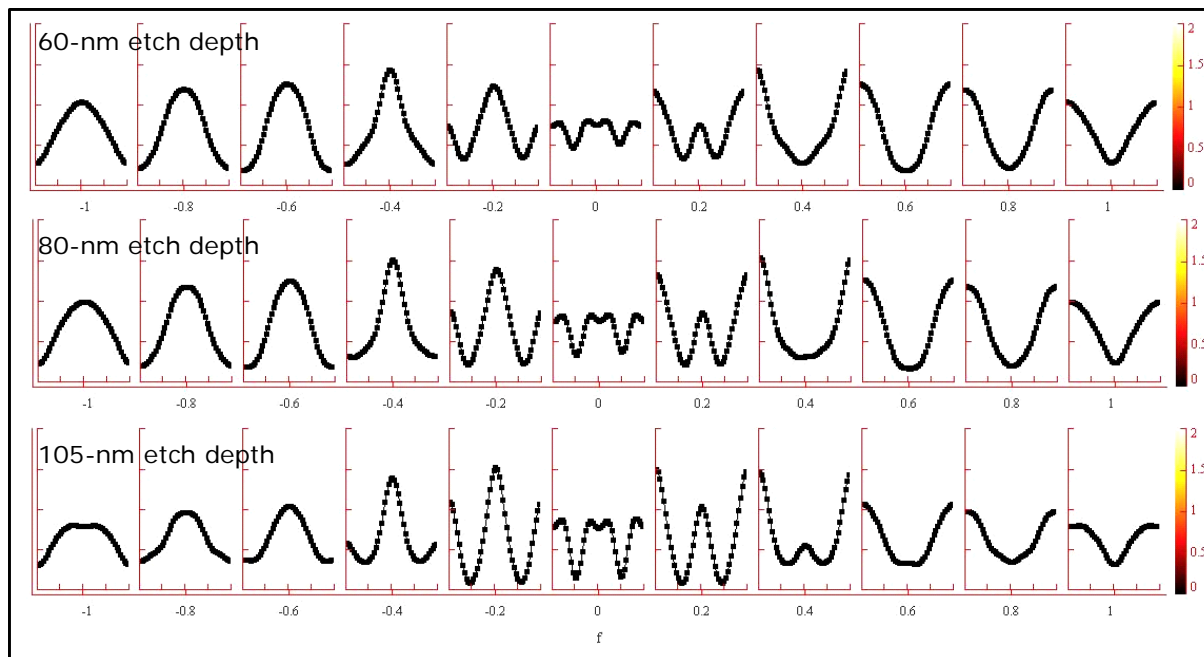
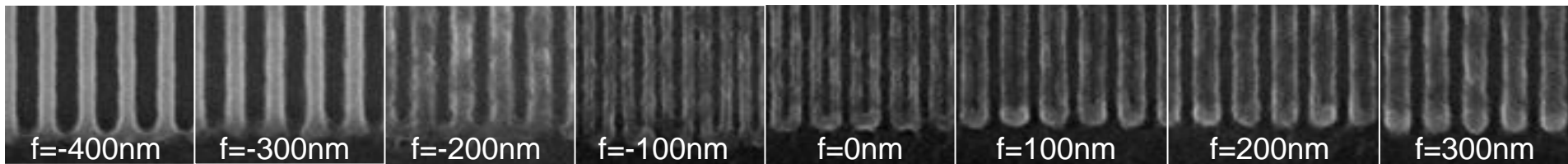


π -shift mask simulations



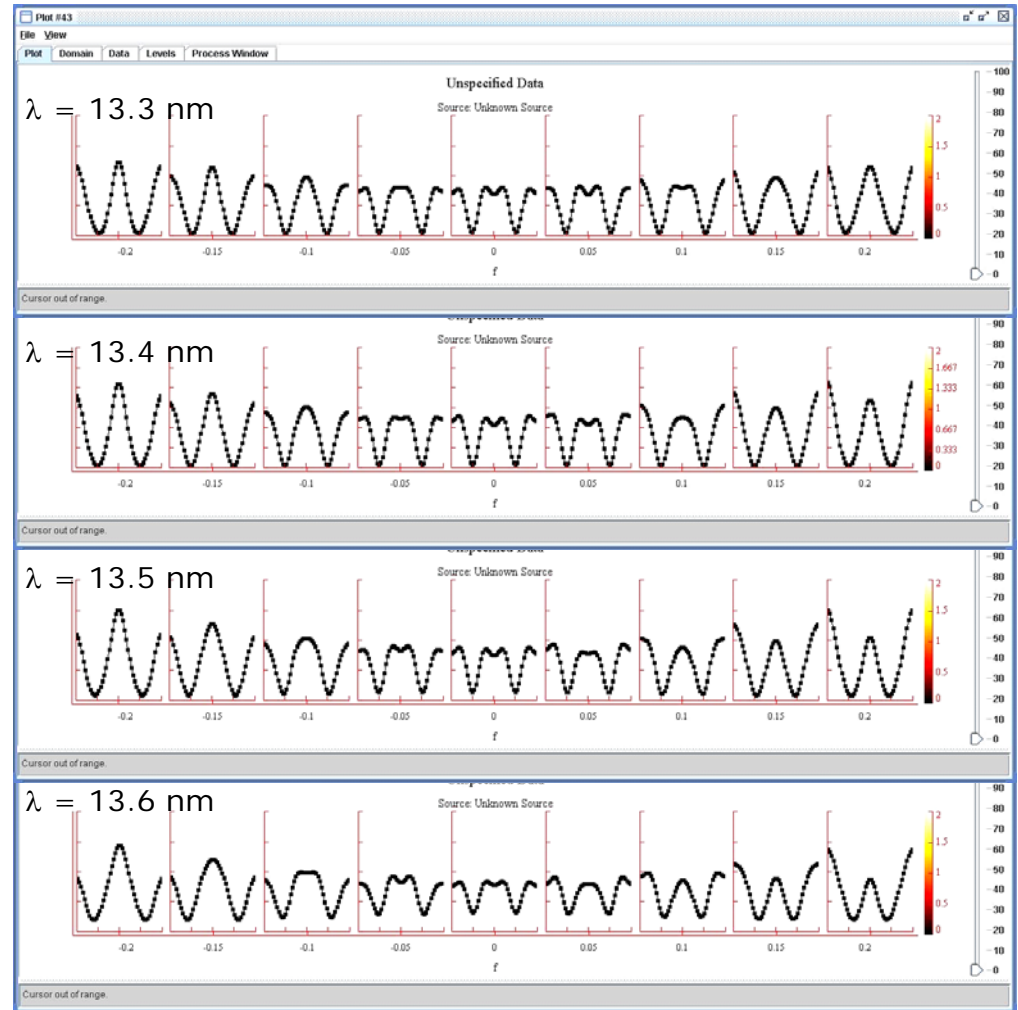
Comparing PSM1 results to simulations

- Simulations using a shallower etch depth are in better agreement with the experimental results



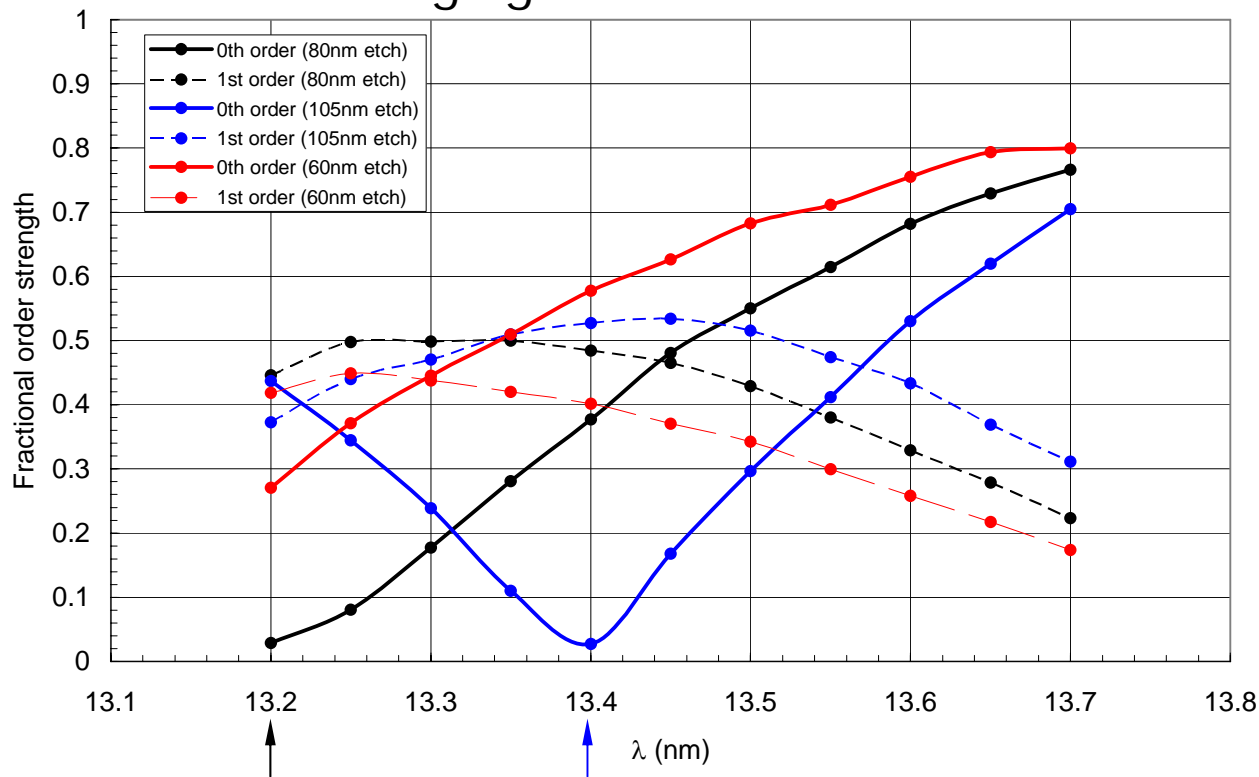
Tuning the spectrum for optimum phase shifting

- Etch depth = 100nm
- Aerial images through focus (± 200 nm)
- Results appear best at ~ 13.4 nm



Simulated at-wavelength reflectance and diffraction

- The simulated response of an etched-multilayer PSM indicates that the 105nm etch depth should be optimized for 13.4 nm imaging

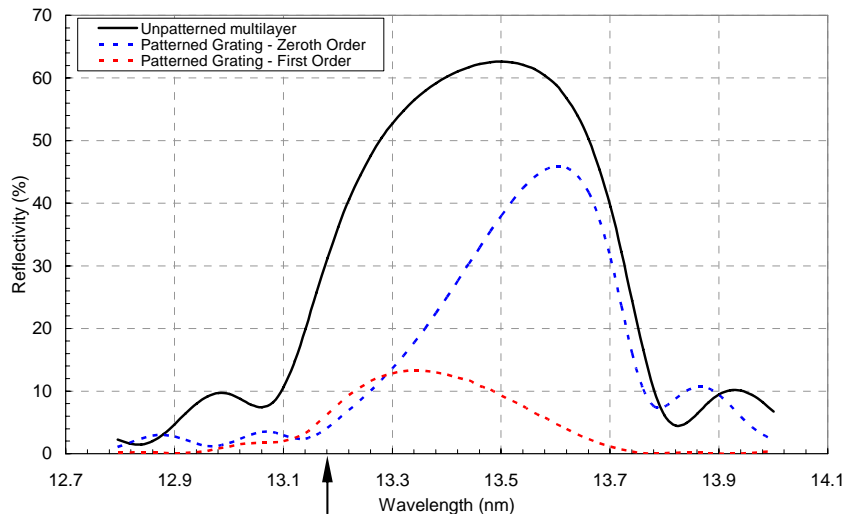


best 1st/0th order ratio best 1st/0th order ratio

At wavelength reflectivity measurements

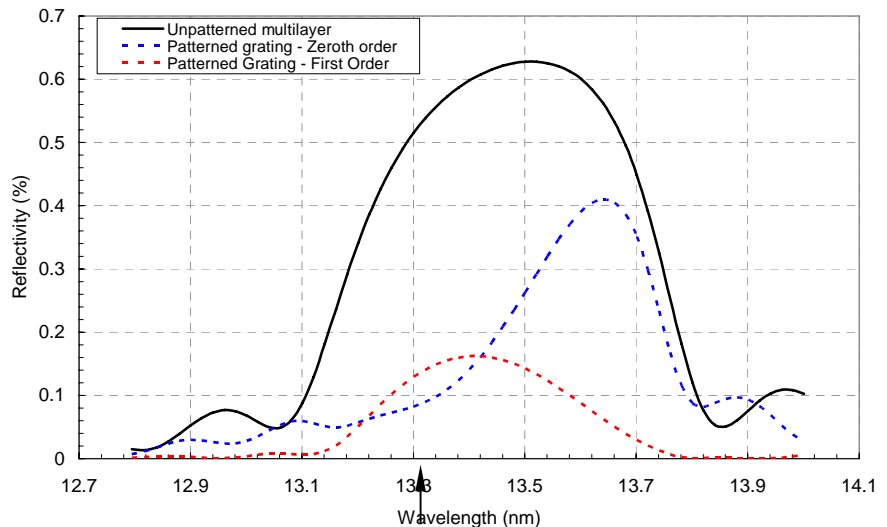
- Measured spectral response of our masks indicates that both PSM1 and PSM3 were under etched
 - These experimental data show first order peaking at a wavelength shorter than 13.4 nm
 - This is consistent with the observed print results, which are the best at 13.3 nm for PSM3
- Notable improvement from PSM1 to PSM3
 - Etch depth of 80nm for PSM1 vs. 105nm for PSM3

Spectral Response of EUV-PSM1



best 1st/0th order ratio

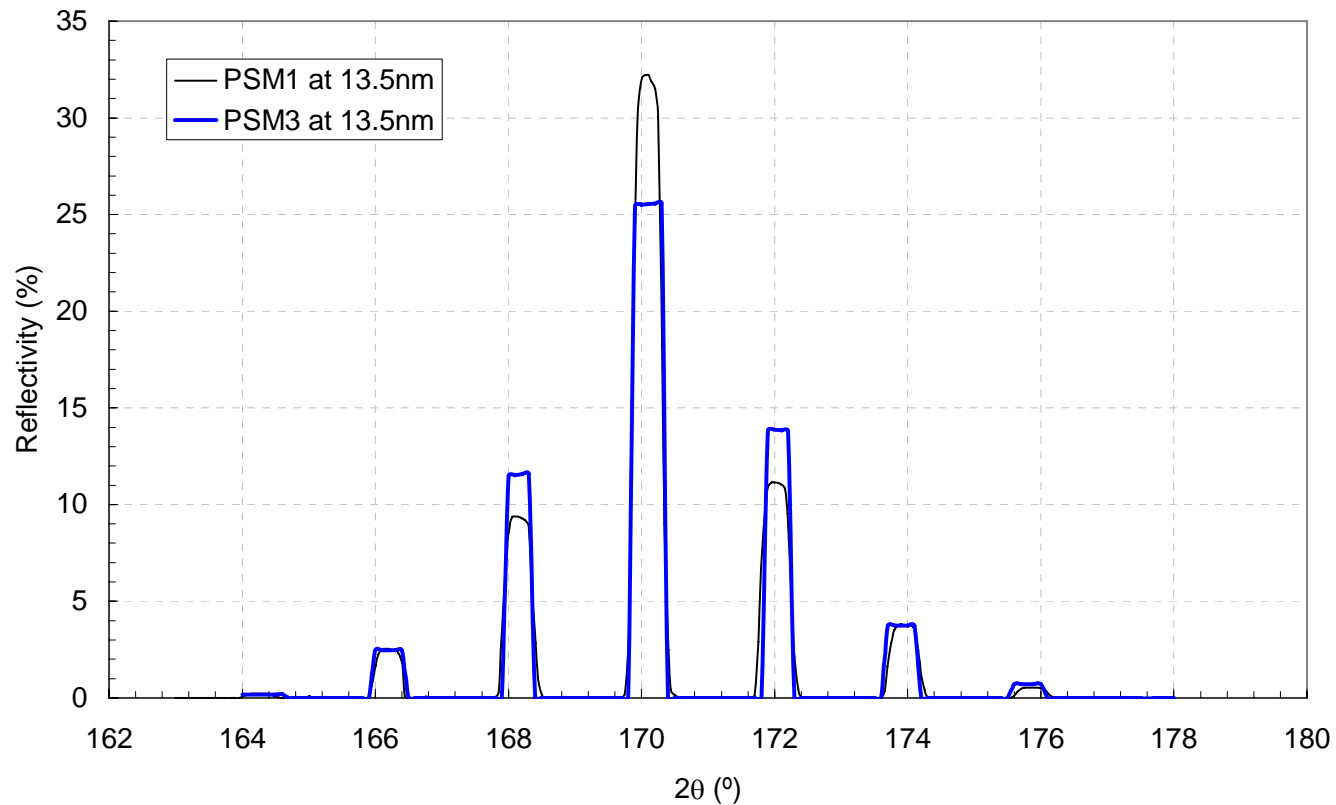
Spectral Response of EUV-PSM3



best 1st/0th order ratio

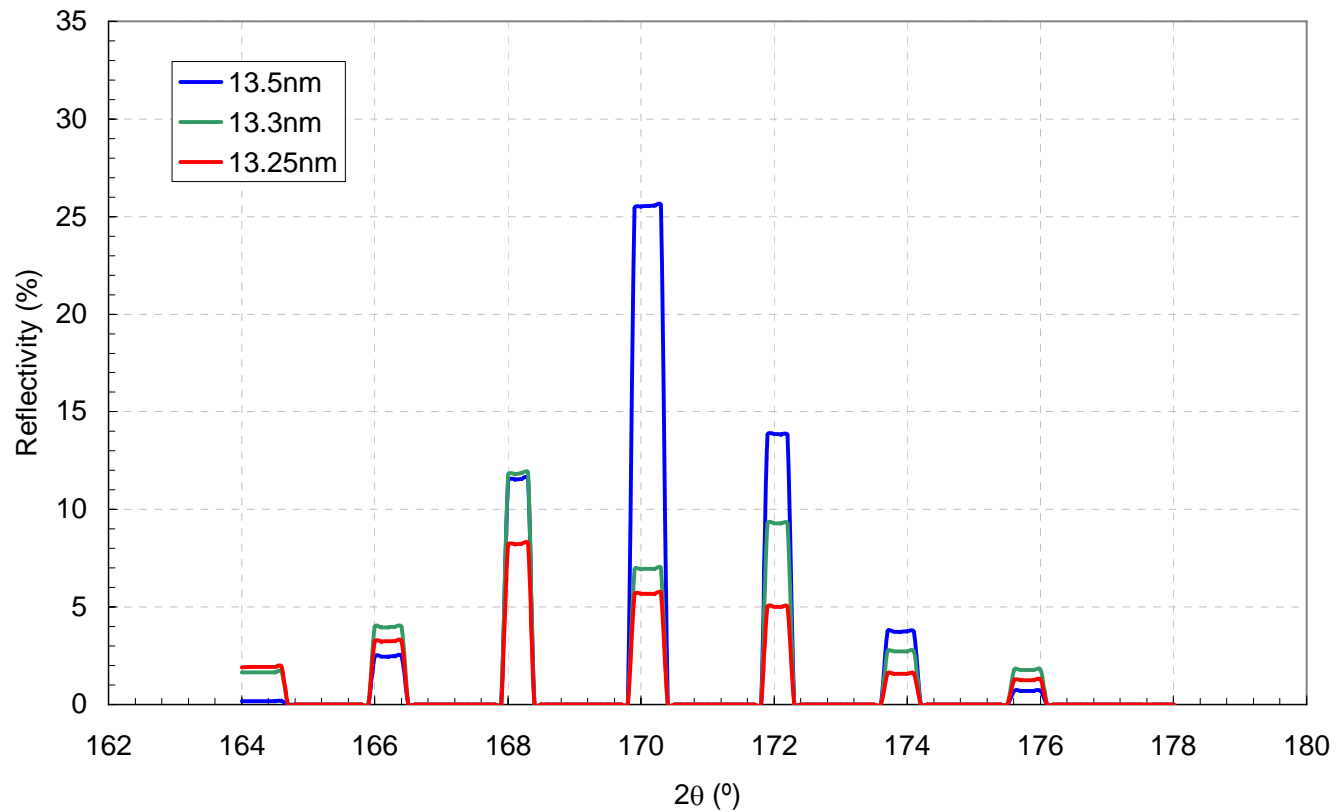
Measured diffracted orders for PSM1 & PSM3

- Diffracted orders measured at 13.5 nm
 - Large contribution from zeroth order consistent with inadequate phase-shifting observed in printing experiments for PSM1



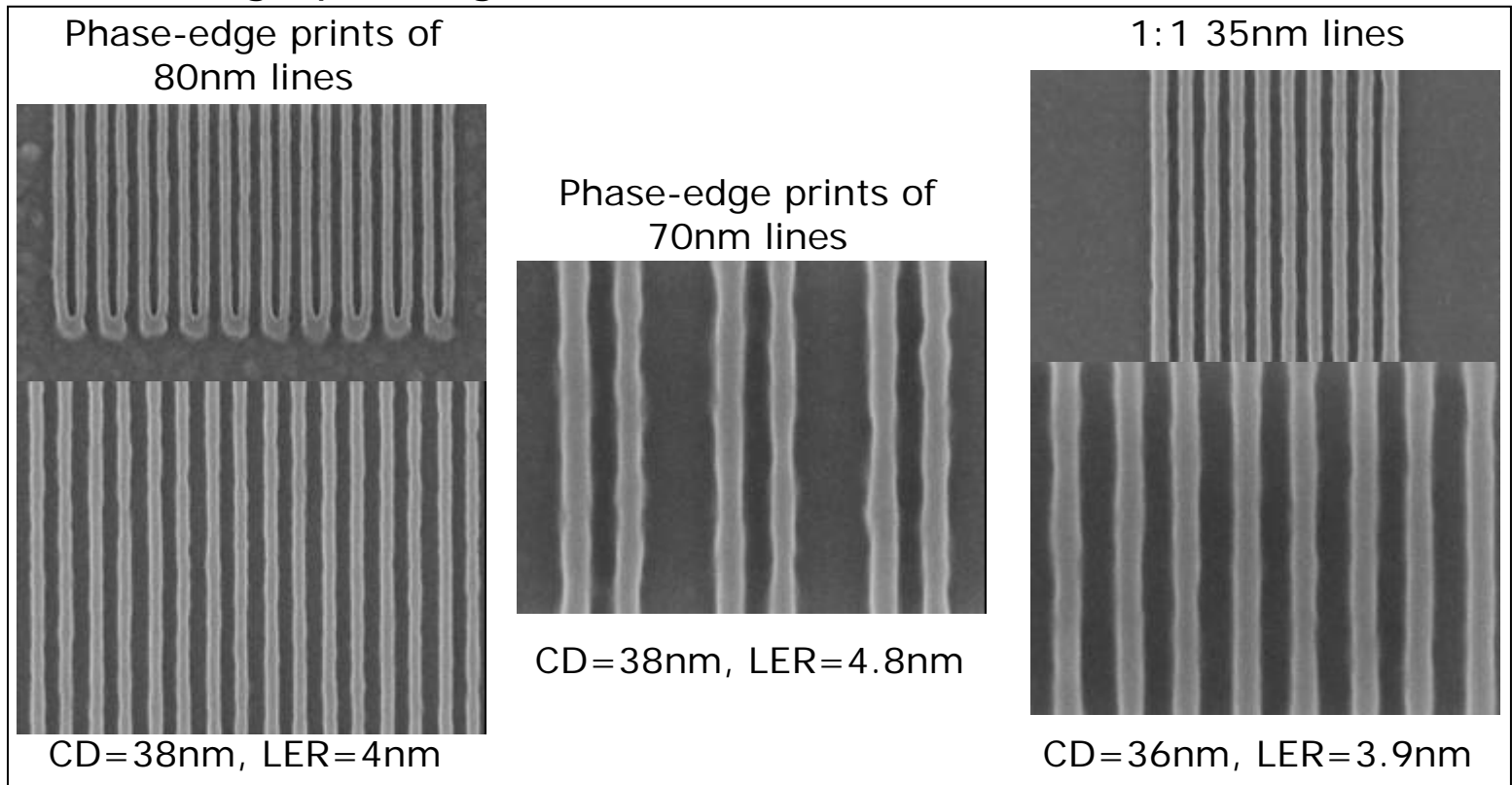
PSM3 diffracted orders through wavelength

- Diffracted orders measured at 13.25 nm, 13.3 nm, and 13.5 nm
 - Much better suppression of zeroth order at 13.3 nm



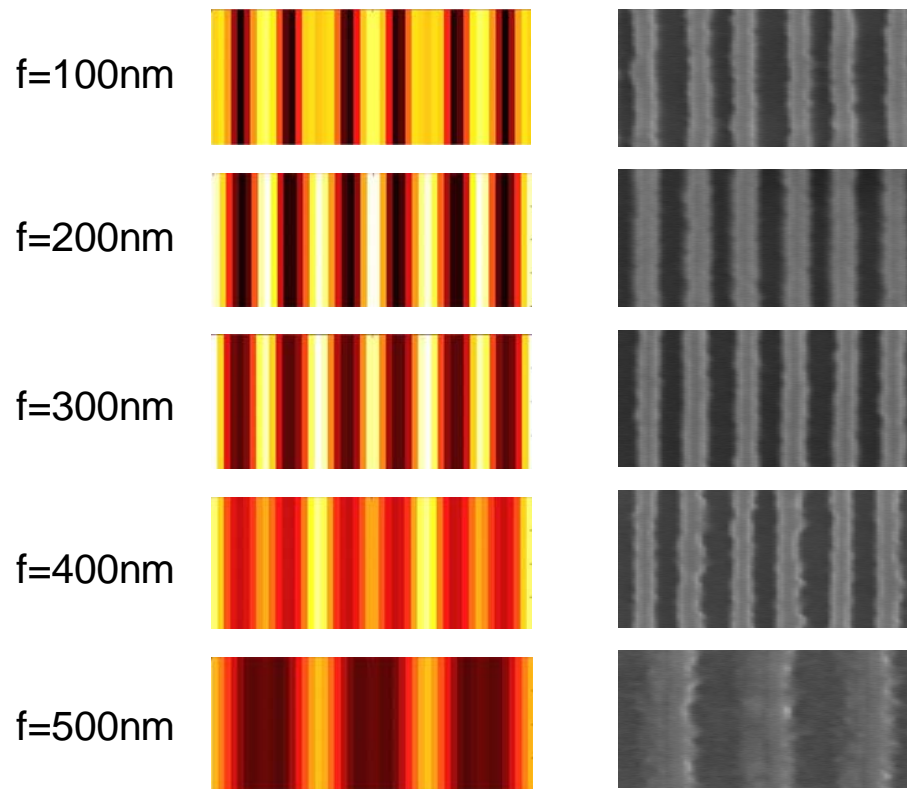
Overview of initial results with PSM3 at $\lambda=13.3$ nm

- Mask: PSM3 with etch depth=105nm
- Illumination: monopole
- Phase-edge printing with excellent resolution and LER



PSM3 mask printing results

- Second 'CPL' mask has 105 nm etch depth
- Prints also match π -phase-shift simulation better
- Images of programmed 1:1 80-nm lines through focus are shown below.



Conclusions and Future Work

- Successful demonstration of the use of EUV phase-shift masks for printing fine resist features
- Phase-shift prints appear to be limited by resist resolution
 - Observed performance is very similar to that of dark-field binary mask, even though the PSM is completely bright
- We are planning to build and test an att-PSM mask next
 - A PGFM mask for focus monitoring will also be fabricated in the future
- Simulations
 - Good qualitative agreement with experiments
 - What is the influence of sidewall angle on the performance of PSMs?
 - What is the effect of biasing or duty cycle?
- Assess degradation over time
 - Early measurements do not reveal any significant reflectance loss
 - Regular measurements of PSM1 and PSM3 have been planned at LBL (ALS)