Design for a stand-alone extreme ultraviolet interference lithography tool

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Motivation

- Photoresist is a major challenge still facing EUV
- Resist development hampered by lack of availability of high-resolution tools
- Interference lithography (IL) is potential pathway to development of low-cost resist-development tools
- Present IL methods require coherent sources
  - **UW:** H. H. Solak, D. He, W. Li, S. Singh-Gasson, F. Cerrina, B. H. Sohn, X. M. Yang, P. F. Nealey, Appl. Phys. Lett., **75**, 2328 (1999).
  - **PSI:** H. H. Solak, J. Phys. D: Appl. Phys. **39**, 171 (2006).
- Stand-alone coherent sources not mature enough to support rapid deployment of IL tools
  - **CU:** X. Zhang, A.R. Libertun, A. Paul, E. Gagnon, S. Backus, I.P. Christov, M.M. Murnane, H.C. Kapteyn, R.A. Bartels, Y. Liu, D.T. Attwood, Opt. Lett. **29**, 1357 (2004).
  - **CSU:** S. Heinbuch, M. Grisham, D. Martz, and J.J. Rocca, Opt. Exp. **13**, 4050 (2005).

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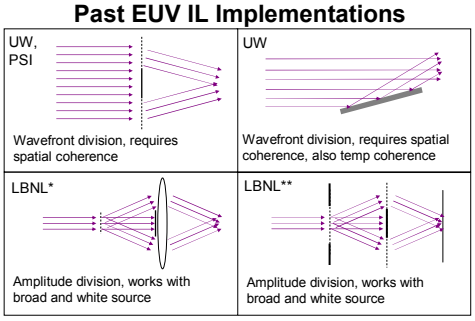
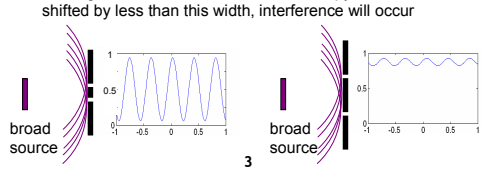
Past EUV IL Implementations



* M. Shumway, S. Lee, H. Cho, P. Naulleau, K. Goldberg, and J. Bokor, Proc. SPIE **4343,** 357-362 (2001).
** M. Wei, D. Attwood, T. Gustafson, and E. Anderson, J. Vac. Sci. Technol. B 12, **3648** (1994).

Spatial Coherence

- Spatial coherence relates to the ability of a wavefront to interfere with a spatially shifted version of itself
- Spatial coherence is often described in terms of Young's double aperture interference experiment (wavefront division system)
  - The maximum separation between the two pinholes while maintaining interference can be viewed as the lateral coherence width
  - As long as a wavefront is mixed with a copy of itself that is shifted by less than this width, interference will occur



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Spatial Coherence

- Analogous to temporal coherence, spatial coherence has a Fourier Transform relationship to the spatial spectrum of the illumination
- Given an incoherent source of a certain size, the only way to increase coherence is to throw away light
- In general, the spatial bandwidth is determined by the angle subtended by the final illuminator optic aperture as viewed from the plane of interest
- For 15W electrodeless Z-pinch source, and reasonable field size and exposure time requirements (3-mm, < 1 sec), the illumination lateral coherence length (W_c) is approximately 275nm
- Given the extremely high cost of EUV photons, throughput concerns are paramount in the development of a low-cost IL tool
  - Choosing relaxed coherence designs is crucial
  - Wavefront division systems are not feasible

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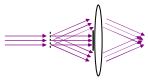
Imaging-optic beam-combiner approach

- Grating used as beam splitter
- Zero-order stop used for two-beam interference



- Can be viewed simply as conventional lithography system
  - Zero-order-stop equivalent to use of chromeless PSM
- From the conventional lithography analogy:
  - Pupil fill must be smaller than the central obscuration
  - Resolution limit = 0.25 λ/NA
  - Obtaining 15-nm lines and spaces with no loss of the assuming σ = 0.1, requires optic NA of 0.25
- Assuming 30% radius central obscuration, we can only tolerate an image-plane coherence width as small as 110 nm
  - This fits well with source capabilities (see slide 4)

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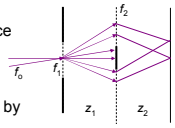
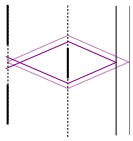
Two-grating Interferometer: Broad Source

- Second grating ~1/2 pitch of first
- Printed pitch = pitch of second grating
- Zero-order stop for two-beam interference
- Shear-free interference enables low spatial coherence
- Geometric pattern shift exactly canceled by relative phase shift of two beams



- Adding defocus causes shear between interfering beams, thus reduced contrast
  - System can emulate focus behavior of conventional lithography system
  - DOF limit when shear equals lateral coherence length
  - Shear proportional grating frequency



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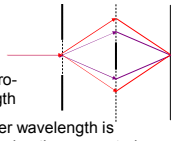
Two-grating Interferometer: White Light

- Despite the highly chromatic properties of gratings, the two-grating interferometer is achromatic
- The geometry of the system causes the zero-shear plane to be independent of wavelength



- The increased interference angle with longer wavelength is exactly canceled out by the wavelength causing the generated fringe pattern to be independent of wavelength
- Above properties can be proven with physical optics analysis

$$I(x) = 2 + 2\cos\{4\pi(f_1 - f_2)x - \pi\lambda z_1[(f_o+f_1)^2 - (f_o - f_1)^2] - \pi\lambda z_2[(f_o+f_1-f_2)^2 - (f_o-f_1+f_2)^2]\}$$

When phase-shift term is independent of f_o and λ, system works with broad source and white light: $\mathbf{z_2 = f_1 z_1/(f_2 - f_1)}$

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Depth of Focus

- **Imaging-optic beam combiner**
  - Same DOF as conventional lithography system with unconventional settings (σ = 0.1 on axis) and a central obscuration larger than the pupil fill
  - *Prolith* modeling predicts 600-nm DOF for 15-nm lines
- **Grating beam combiner**
  - Shear analysis:
    - T_2 = 30-nm $\rightarrow$ 26° relative shear angle
    - DOF = W_c/tan(26°) = 564 nm
  - Physical optics analysis (place constraints on phase-shift term):
    - Max phase shift at max $f_o = \pi/2$
    - Solve for $z_1 - z_2$ and define DOF as $2(z_1 - z_2)$: DOF = 500 nm
- Both methods have ~ same DOF (note that imaging optic method can also be described from the shear perspective)

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Modeling

- **Imaging-optic beam combiner**
  - Conventional litho modeling tools such as *Prolith* can be used
- **Grating beam combiner**
  - New physical optics modeling code developed specifically to treat the two-grating interferometer
  - Modeling code includes ability to efficiently treat grating imperfections including relatively high-frequency grating noise and efficiently treat the problem in 2D model
  - Model can be used to determine and/or verify grating fabrication and alignment specifications
  - Model can also be used to study the impact of illumination
  - Modeling has verified 100% fringe contrast under partially coherent illumination for aligned system
  - Modeling has verified 600-nm DOF based on parameters above

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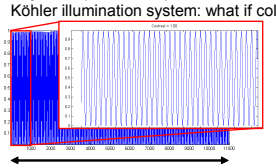
Impact of Illumination Collimation Errors

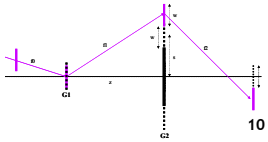
- Physical optics description above seems to require a collimating Köhler illumination system: what if collimation is not perfect?



4 mm

Modeling results for divergent illumination (100-mm radius). Collimation not required for system to work. Modeling also shows no change in DOF.

Determination of Relevant Grating Noise



- Only need to consider limited frequency band
- Relevant frequency error half band is:

$$\Delta_f = \frac{NA}{\lambda} + \frac{w}{\lambda z}$$

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Efficiency

- Predicted efficiency for example two-grating configuration

collection efficiency	0.015192247	collection angle= 10 degrees
M1 (illuminator)	0.65	
M2 (illuminator)	0.65	
M3 (illuminator)	0.65	
M4 (illuminator)	0.65	
Polarization loss	0.5	
grating 1 membrane	0.5	100-nm Nitride membrane
grating 1 diffraction	0.405284735	binary amplitude (consider efficiency of bright areas only)
grating 2 membrane	0.5	100-nm Nitride membrane
grating 2 diffraction	0.405284735	
TOTAL	**5.57E-05**	

input power	15000 mW
power at wafer	8.35E-01 mW
area at wafer	0.36 cm^2
wafer power density	2.320 mW/cm^2

Exposure time 4.3 seconds for 10 mJ/cm^2 resist

- For imaging-optic beam-combiner, we replace the second grating losses with two multilayer reflections
- Although, in principle, we also benefit from the demagnification, we require stitching to make the field size at least 1 mm
- This yields 1.5-second exposure time ignoring stage effects

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Summary

- Ultra-high-resolution interference lithography with stand-alone incoherent sources is possible
- Presently used single-grating configuration is not feasible with incoherent sources
- Two potential broad-source, white light, systems have been described here
- Both systems have very workable depth of focus and enable defocus allowing traditional process analysis to be performed
- Both systems enable simultaneous printing of multiple pitches
  - Two-grating case supports larger pitches
- Conventional modeling tools can be used for imaging-optic beam-combiner
- New modeling code developed for the detailed analysis of the two-grating interferometer

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