A SHARP LOOK AT FUTURE NODES OF EUV LITHOGRAPHY

SHARP High-NA actinic Reticle Review Project

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Source angular spectrum

Aperture
Fourier synthesis illuminator

Zoneplate lens
Illuminator angular range

- 0.625 4xNA
- 10° CRA
- σ=0.8

σ=1 outline
Pupil fill

- Conventional
- 0.33 4xNA, 6° CRA

Liu, SPIE 90480Q (2014)
Pupil fill

- Crosspole
- 0.33 4xNA, 6° CRA

Liu, SPIE 90480Q (2014)
Pupil fill

- Crosspole
- 0.33 4xNA, 6° CRA

Liu, SPIE 90480Q (2014)

Modulation of flux in pupil channels
Pupil fill

- Quasar
- 0.33 4xNA, 6° CRA

Liu, SPIE 90480Q (2014)
Pupil fill

- Freeform Source
- 0.33 4xNA, 6° CRA

Pupil diagram
- Gold pattern on Si$_3$N$_4$-membranes
- Magnetic mounting
- Kinematic positioning
Zoneplates

Standard Zoneplates:
- 0.25 to 0.625 4xNA
- 6° to 10° CRA
- 5 azimuthal angles

Chip B
- Zernike Phase Contrast
- Differential Interference Contrast
- Stereoscopic imaging
- Cubic Phase Modulation

0.625 4xNA:
- 22-nm hp resolution on the mask
- 5.5 nm hp resolution wafer scale (for a 4x system)
Zoneplates

Standard Zoneplates:
- 0.25 to 0.625 4xNA
- 6° to 10° CRA
- 5 azimuthal angles

Chip B
- Zernike Phase Contrast
- Differential Interference Contrast
- Stereoscopic imaging
- Cubic Phase Modulation

Chip C
- Elliptical zoneplates
Thin-absorber wafer mask

40-nm Nickel absorber
Chrome
Ruthenium
Mo/Si Multilayer
Silicon wafer

Thin-absorber wafer mask
Comparison of absorbers

Future Study
- Two photomasks with identical patterns
- Mask SEM characterization
Comparison of absorbers

Initial Study

- Identify comparable patterns on available photomasks
Patterns

- 0.33 4x NA
- Quasar illumination
- 22.5 nm CD (1x)

- 200 nm (1x)
- Ta-based
- Nickel
Patterns

- 0.55 4x/8x NA
- Quasar illumination
- 12.5 nm CD (1x)

- Ta-based V
- Ta-based H
- Nickel
Contrast and NILS

- Ta-based
- Nickel
- 200 nm (1x)
- 22.5 nm CD (1x)
- 0.33 4x NA
- Quasar illumination
Contrast and NILS

- Ta-based
- Nickel
- 0.33 4x NA
- Quasar illumination
Contrast and NILS

0.33 4xNA:
- higher on vertical features

- 0.33 4x NA
- Nickel
Contrast and NILS

- 200 nm (1x)
  - 0.33 4x NA
  - higher contrast in V

- 100 nm (1x)
  - 0.55 4x/8x NA
  - higher contrast in H
Contrast and NILS

- 0.33 4x NA
- higher contrast in V

- 0.55 4x/8x NA
- higher contrast in H
Optimized source

- 0.33 4xNA, regular mask
- balanced Quasar

- 0.33 4xNA, regular mask
- imbalanced Quasar
Optimized source

- 0.33 4xNA, Ta-based balanced Quasar

- 22.5 nm CD (1x)
- 200 nm (1x)

- 0.33 4xNA, Ta-based imbalanced Quasar
Optimized source

Imbalanced Quasar:
- higher NILS for both grating orientations
- wider focus range
Source Optimization

- Pupil Channel $\alpha$
Source Optimization

- Pupil Channel $\alpha$
- Image $i_\alpha$
Source Optimization

- Pupil Channel $\alpha$
Source Optimization

- Pupil Channel $\alpha$

- Image $i_\alpha$
Source Optimization

- Pupil Channel $\alpha$
- Image $i_a$
Source Optimization

- Pupil Channel $\alpha$
- Image $i_\alpha$
Source Optimization

- Pupil Channel $\alpha$
- Image $i_{\alpha}$
Source Optimization

- Pupil Channel $\alpha$
- Image $i_\alpha$
Source Optimization

- Pupil
Source Optimization

- Pupil

- Image $I = i_a$
Source Optimization

- Pupil

- Image $I = \sum_i a_i$
Source Optimization

- Pupil

- Image $I = \sum_{a} i_a$
Source Optimization

- Quasar

- 40-nm (1x) dense contacts
Source Optimization

- Quasar

- 40-nm (1x) dense contacts
Source Optimization

- Quasar
- Freeform Source

- 40-nm (1x) dense contacts
Source Optimization

- Quasar
- Freeform Source
- 40-nm (1x) dense contacts
Summary

SHARP High-NA Actinic Reticle Review Project

- Emulation of imaging in EUV scanner
- Emulation of anamorphic imaging
- Increased imaging performance with thinner absorber both for 0.33 and 0.55 anamorphic
- Source Optimization demonstration
Thanks to our users.

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Thanks to our users.

Thanks to INTEL for funding SHARP operations.

Thank you!
AIS: Characterization of aberrations

- Through-focus image data of 4 grating orientations and 12 monopole illuminations

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- Aberrations solved from measured focus shifts using least-squares approach

90° (3 points)

0° (3 points)

135° (3 points)

45° (3 points)
Field dependent aberrations

- Ideal 0.33 4xNA zoneplate
- AIS measurement

Sweet spot ($Z_4$ to $Z_8$) : $7.2 \text{ m}\lambda$ RMS ($\lambda_{\text{EUV}}/139$)
Field dependent aberrations

Latest measurement
Sweet spot ($Z_4$ to $Z_8$): \(4.4 \text{ m} \lambda\) RMS

- Ideal 0.33 4xNA zoneplate
Programmed aberrations

Astigmatism zoneplate

Coma zoneplate

Spherical aberration zoneplate

Mixed Zernike zoneplate
Programmed aberrations

Astigmatism zoneplate

RMS error: 3.2 mλ (0.043 nm)

Coma zoneplate

RMS error: 4.1 mλ (0.055 nm)

Spherical aberration zoneplate

RMS error: 5.2 mλ (0.070 nm)

Mixed Zernike zoneplate

RMS error: 4.8 mλ (0.065 nm)