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Binary Pseudo Random Array standard for Extreme Ultraviolet Lithography tool characterization

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Abstract. Extreme ultraviolet (EUV) imaging tools play a crucial role in EUV lithography. Achieving high accuracy in EUV metrology is essential for advanced semiconductor manufacturing. Thorough characterization of the instrumentation in use is required. Binary Pseudo Random Arrays (BPRA) are an established standard for calibrating and characterizing optical instruments in the frequency domain. This work expands the BPRA standard to applications in EUV imaging. To extend the technology to the EUV spectral range, a high-resolution BPRA target with a smallest feature size of 40-nm is developed. The EUV BPRA target establishes an in-situ and portable calibration and alignment standard for EUV imaging. The target is patterned by means of electron-beam lithography, using a nickel absorber with a thickness of 39 nm. The substrate is a 4" silicon wafer with a molybdenum/silicon multilayer coating. To demonstrate the efficacy of the target and develop the instrument calibration protocol, the target is imaged on the SHARP EUV mask microscope. Power Spectral Density (PSD) data are presented. The characteristics of the imaging system are imprinted on the PSD. The Modulation Transfer Function (MTF) is extracted from the PSD data. A partially coherent imaging model is used as a reference to the experimental results.

Keywords: Binary Pseudo Random Array, BPRA, EUV mask, photomask, SHARP, partially coherent imaging, MTF, modulation transfer function.

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1 Introduction

Extreme Ultraviolet (EUV) lithography entered high-volume manufacturing in 2019. The most advanced chips, often containing tens of billions of transistors, are produced using this technology.

To produce a chip, patterns need to be transferred to the wafer from a set of photomasks in a series of exposures. The 3-nm technology node contains about 20 EUV layers. The lithographic process has to be more or less free of errors and the photomasks have to be defect free. The semiconductor industry uses a variety of EUV imaging tools¹⁻³ to assess the performance of a mask blank or photomask, identify defects, or verify the printability of a feature after repair. EUV imaging tools are also used in research and development towards future nodes of EUV lithography and for the evaluation of advanced mask architectures and absorber materials.^{4,5} Such instruments play a crucial role in EUV lithography. In order to obtain accurate results at all times and assure seamless integration into the lithographic process, the imaging performance of these instruments has to be closely monitored. A variety of imaging tests are used across the industry, often involving proprietary patterns, techniques or metrics, making it difficult to share, discuss and compare results.

Binary Pseudo Random Arrays (BPRA) and the corresponding metrology framework are a well-established standard for calibrating microscopes, interferometers, surface profilers and other optical instruments.⁶⁻⁸ BPRAs feature a flat power spectral density (PSD). The modulation transfer function (MTF) of the instrument under investigation can be extracted from the measured image PSD and inherent PSD of the target.

This work expands the BPRA metrology standard to EUV imaging. A BPRA target on an EUV photomask provides a portable in-situ calibration standard for characterizing EUV imaging tools in the frequency domain. Such a standard enables monitoring the imaging performance of an instrument over time, comparing different instruments, or evaluating different copies of the same instrument at different locations.

2 Target Fabrication

To allow for an accurate calibration across the entire spatial-frequency range of the instrument, the smallest feature size of a BPRA should be smaller than the resolution limit of the instrument. For a diffraction-limited imaging system using off-axis illumination, the resolution limit (smallest critical dimension CD) is given by: $CD = 0.25 \cdot (\lambda/NA)$. The corresponding spatial frequency is $1/(2CD) = 2NA/\lambda$. For the 0.33 numerical-aperture (NA) generation of EUV lithography⁹ (at a wavelength λ of 13.5 nm), the smallest CD is ~10 nm. For the 0.55 High-NA generation of EUV lithography,¹⁰ currently under development, the smallest CD is ~6 nm. The corresponding mask-

side feature sizes (at 4x demagnification from the mask to the wafer) are 40 nm for the current 0.33NA generation and 24 nm at High-NA.

EUV photomasks work in reflection. To achieve useful reflectivity at a wavelength of 13.5 nm, a multilayer coating is required. The photomask consists of a 6" x 6" flat glass substrate with a Molybdenum/Silicon multilayer coating and an absorber material on top. Electron-beam lithography is used to pattern the absorber. Photomasks can be patterned at a commercial mask house but the cost is outside the scope of the work presented here. The EUV BPRA prototype uses a 4" silicon wafer as a substrate. Wafers meeting the roughness requirement for EUV imaging are readily available and the overall flatness of the substrate is not a concern for the application since the target pattern size is well below 100 μm . The standard EUV absorber material is tantalum boron nitride (TaBN)¹¹ with a thickness in the range of 60 nm to 70 nm. Alternative absorber materials are a subject of active research.^{12,13} At a feature size of 40 nm, a 60-nm thick absorber layer is taller than the width of the feature. To separate the illuminating and imaging ray cones in EUV lithography, the mask is illuminated at, and imaged from an angle of six degrees to the surface normal. (High-NA EUV lithography uses a slightly smaller angle.) The 3D nature of the absorber pattern on top of the multilayer and the oblique illumination cause mask 3D effects that negatively impact the aerial image. High-k absorber materials with an increased absorption can achieve contrast similar to TaBN at a reduced film thickness. The letter k represents the extinction coefficient of the material. Mask 3D effects are reduced and the image fidelity is increased for a range of patterns and imaging conditions. Nickel is one of the high-k absorber materials under consideration for EUV photomasks. Having access to a suitable patterning process, nickel is chosen as the absorber material for the EUV BPRA target. Both the absorption and the phase shift within the absorber layer affect the contrast of a photomask. Taking both mechanisms into account, an absorber thickness of 39 nm is targeted for the EUV BPRA standard.

The resist is patterned using electron-beam lithography in a lift-off process. A smallest feature size of 40 nm is used for the first iteration of the EUV BPRA target. Figure 1 shows an electron-microscopic image of a region within the BPRA with a smallest feature size of 40 nm, displaying adequate pattern fidelity. A smallest feature size of 40 nm is state of the art for EUV photomasks. Smaller feature sizes are required for future nodes of EUV lithography, and for applications like sub-resolution assist features. For the next iteration of the EUV BPRA standard, a smallest feature size of 20 nm is targeted.

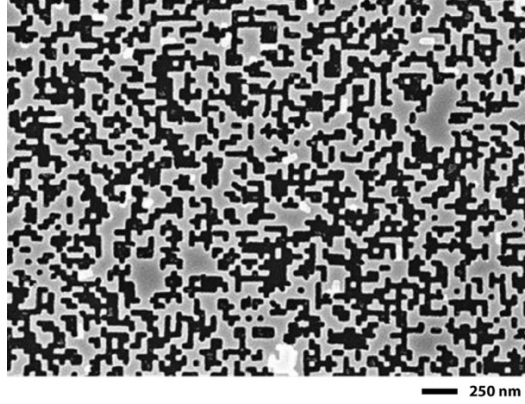


Fig. 1 Scanning-electron microscopic image, showing a region of the BPR target with a smallest feature size of 40 nm. The target is patterned using a 39-nm thick nickel absorber on a 4" silicon wafer with a molybdenum/silicon multilayer coating.

3 Model of the Apparent Modulation Transfer Function

In this section, an imaging model is discussed as a reference for the experimental results, presented in section 4. The illumination used in EUV lithography should be treated as partially coherent. In the EUV scanner, light from a plasma source is collected and directed at the photomask by an illuminator. The illuminator controls the source angular spectrum of the illumination, or pupil fill. Within the optical train, the light is reflected by a number of multilayer mirrors with a narrow spectral bandwidth. Therefore, the light is quasi-monochromatic. EUV imaging tools may use technologies different from the EUV scanner to control the source angular spectrum, but the characteristics of the illumination at the photomask remain the same.

The source angular spectrum of the illumination defines the coherence properties of the light. In EUV lithography, the pupil fill is tailored to the characteristics of the pattern to be printed. There are standard pupil fills¹⁴ that provide adequate imaging performance for common lithographic patterns. The pattern to be printed and pupil fill can also be co-optimized (source mask optimization¹⁴), leading to a unique freeform pupil fill providing the highest imaging performance for the metric targeted in the optimization.

Hopkins' method is a commonly used formulation of partially coherent imaging. It involves a function called transmission cross coefficient (TCC). In the literature, often the intensity of the image is discussed as a function of the transmission cross coefficient. Goodman¹⁵ discusses the image intensity spectrum, or power spectral density F_I as a function of the TCC.

$$F_I(f'', g'') = TCC \cdot \iint_{-\infty}^{\infty} A(f', g') \cdot A^*(f' - f'', g' - g'') df' dg' \quad (1)$$

$$TCC(f', g', f'', g'') = \iint_{-\infty}^{\infty} S(f, g) P(f' - f, g' - g) P^*(f' - f - f'', g' - g - g'') df dg \quad (2)$$

Symbol A represents the object amplitude spectrum. The integral in Eq. (1) corresponds to the object intensity spectrum, or object power spectral density. The TCC contains the source angular spectrum S , pupil function P of the imaging system, and the complex conjugate of the pupil function. The TCC describes the properties of the imaging system and illumination. It is independent of the object. For a circular, binary, and real source angular spectrum and pupil function, the TCC corresponds to the normalized area of overlap of three circles S , P , and P^* in the frequency domain.¹⁵

If the object PSD is constant over a spatial frequency domain larger than the resolution limit of the imaging system, the image PSD is an instance of the TCC. If the object PSD is known, an instance of the TCC can be computed from the image PSD.

The TCC is a function of four spatial frequencies, making it computationally intensive and inconvenient. In response, Kintner¹⁶ introduces function $Q(f', g') = TCC(f', g', 0, 0)$. He points out that despite not offering a complete description of partially coherent imaging, function Q correctly describes the edge response of a partially coherent imaging system in terms of intensity. Since the edge response is closely related to the point spread function and MTF of an imaging system, function Q is useful for the description of a partially coherent imaging system. If the pupil function is circular, binary, and real, and the extent of the source angular spectrum is limited to the size of the pupil, Q corresponds to the cross correlation between the source angular spectrum and the pupil. At the incoherent limit, where the source angular spectrum is uniform and the same size as the pupil, Q equals to the MTF of an incoherent imaging system. At the coherent limit, where the source angular spectrum is the delta function, Q equals to the amplitude transfer function of a coherent imaging system. In many optical instruments, the illumination has a uniform source angular spectrum with an angular extent smaller than the pupil. The ratio between the angular extent of the illumination pupil and imaging pupil is commonly described by the parameter σ . The coherent limit corresponds to a σ of zero and the incoherent limit corresponds to a σ of 1.

The concept of a transfer function applies to linear systems. Incoherent imaging systems are linear in intensity. Coherent imaging systems are linear in amplitude. Partially coherent imaging is not linear. The term apparent MTF can be used to refer to partially coherent imaging systems. It describes an instance of the modulation transfer, realized for a given system, object and

illumination. Figure 2 shows the cross correlation between the source angular spectrum and
imaging pupil for a partially coherent imaging system with a σ of 0.5. The apparent MTF of the
system is a cross-section through the 2D cross correlation.

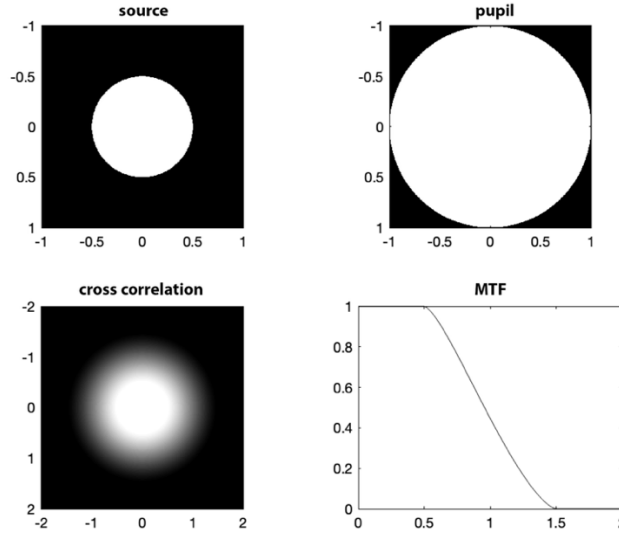


Fig. 2 Partially coherent imaging model: source angular spectrum, imaging pupil, cross correlation of the source
and pupil, and corresponding apparent modulation transfer function.

Figure 3 shows the apparent MTF curves for a number of imaging systems with σ values from
zero to one, computed using this approach. Similar plots of the apparent MTF for imaging systems
described by parameter σ can be found across the literature, e.g., in Ref. 17. The cross correlation
between the source angular spectrum and the pupil can also be used to describe imaging systems
with a non-circular source angular spectrum or pupil shape.

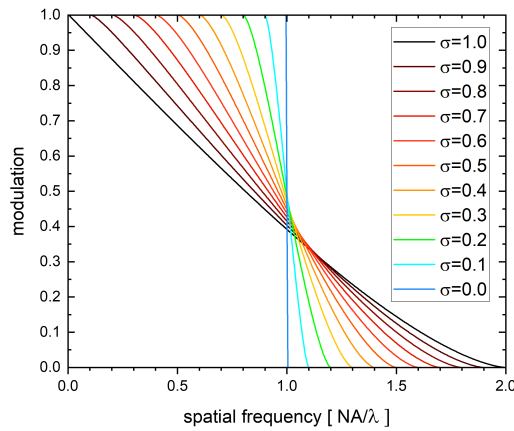


Fig. 3 Apparent modulation transfer functions of a partially coherent imaging system with illumination σ values
from zero to one.

4 Imaging Results

The Sharp Hyper-NA Actinic Reticle Review Project (SHARP)¹⁸ is an actinic EUV photomask microscope at beamline 11.3.2 of the Advanced Light Source at Lawrence Berkeley National Laboratory. The instrument was commissioned in 2013, before the introduction of EUV lithography into high-volume manufacturing. SHARP is designed to advance research and development in EUV lithography and photomask technology. The instrument is a full-field microscope using Fresnel zoneplate lenses as imaging optics and a Fourier synthesis illuminator to produce arbitrary source angular spectra. SHARP emulates the image formation in current and future EUV scanners and other EUV instruments by matching the source angular spectrum and mask-side imaging pupil.

The use of the EUV BPRA standard is demonstrated on the SHARP microscope. The wafer target is mounted on top of a mask substrate and then imaged on the tool. Image data are recorded using different pupil fills and two different zoneplate lenses. One of the zoneplates matches the mask-side NA of the 0.33NA EUV scanner. The other zoneplate matches the mask-side NA of the 0.55 High-NA EUV scanner. The 0.33NA scanner works at 4x demagnification from the mask to the wafer. The 0.55NA scanner uses an anamorphic imaging system with a 4x demagnification in the x-direction, and 8x demagnification in the y-direction. The mask-side pupil is an ellipse. The system also has a central obscuration with an angular extent of 0.2σ . The two zoneplates are referred to as the 0.33 4xNA zoneplate, and 0.55 4x/8xNA zoneplate.

As the BPRA target is imaged onto a pixelated image sensor, the pattern is resampled. If the pixel size of the image sensor, projected onto the object plane, is smaller than the smallest feature size CD of the BPRA (i.e., oversampling), the flat PSD of the array is transferred to a sinc-square shaped resampled PSD_S :¹⁹

$$PSD_S = \left(\frac{\sin(\pi \cdot CD \cdot f)}{\pi \cdot CD \cdot f} \right)^2 \quad (1)$$

The reshaping of the PSD is separate from the impact of the imaging system. Figure 4 shows the resampled PSD_S of the BPRA target with a CD of 40 nm. Resampling reduces the PSD for spatial frequencies below the maximum spatial frequency $1/(2CD)$ of the original array. At $1/(2CD)$, PSD_S has a value of 0.4. Spatial-frequency content is added above $1/(2CD)$. The spatial frequencies $2NA/\lambda$, corresponding to the resolution limits of the 0.33 4xNA zoneplate (NA_1) and 0.55 4x/8xNA zoneplate (NA_2) are marked on the plot. For the 0.55 4x/8xNA zoneplate, the

resolution limit in the x-direction is used. It is worth noting that PSD_S does not depend on the projected pixel size of the image sensor, as long as it is smaller than the minimum feature size of the array.

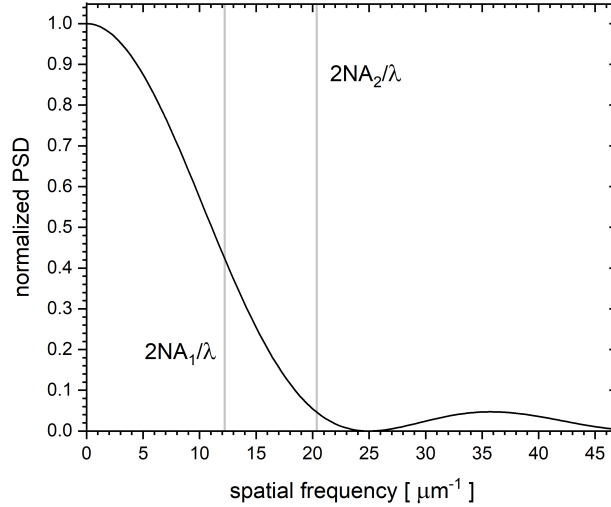


Fig. 4 Power spectral density of a binary pseudo random array with a smallest feature size of 40 nm, resampled to a projected pixel size of less than 40 nm.

At the resolution limit of the 0.33 4xNA zoneplate, PSD_S is above 0.4. The BPRA target is suitable for the 0.33NA generation of EUV lithography. At the resolution limit of the 0.55 4x/8xNA zoneplate, PSD_S is below 0.05. The CD of the BPRA target is insufficient for High-NA EUV imaging. Since the resolution limit of the 0.55 4x/8xNA zoneplate lies before the first zero point of the sinc-square function, the BPRA target can be used for a High-NA imaging demonstration with limited accuracy.

Linear-scale false-color PSD data, computed from SHARP image data of the BPRA target, are shown in Figure 5. To remove the impact of resampling on the spectra, the raw PSD data are divided by PSD_S . The spectra are distinctly different. The properties of the imaging system and illumination are imprinted on the spectra, including the shape of the aperture, presence of a central obscuration, and the source angular spectrum. The spectra show the resolving power of the corresponding imaging configurations in two dimensions. Aberrations, misalignment, and inaccuracies in the pupil fill or aperture shape show in the PSD data. The spectra in the first column of Figure 5 are recorded using coherent illumination ($\sigma \approx 0$). The measured PSD is expected to reproduce the shape of the corresponding imaging pupil. For the 0.55 4x/8xNA zoneplate, the

central obscuration blocks the zero diffraction order for on-axis illumination. This causes frequency doubling in the image. The resulting PSD matches the corresponding pupil shape but is twice as large in the frequency domain.

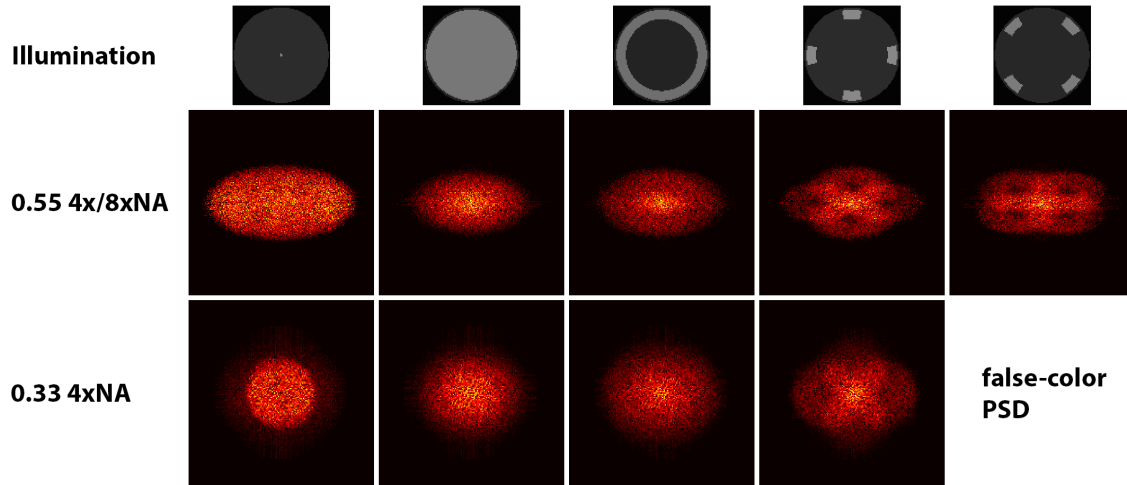


Fig. 5 Linear-scale false-color power spectra of image data of the binary pseudo random array target, imaged on the SHARP EUV microscope, using different zoneplate lenses and pupil fills.

Figure 6 shows the cross correlation between the pupil of the 0.33 4xNA zoneplate and a pupil fill called quasar illuminator. The measured PSD for this imaging configuration, corrected for resampling, is shown next to the cross correlation. There is qualitative agreement between the model and measured data. The measured spectrum shows a reduction in power for higher spatial frequencies. The corresponding loss in modulation is more pronounced in the y-direction. In this case, the loss in modulation is caused by chromatic aberration. The SHARP microscope uses zoneplate lenses in an off-axis configuration. These zoneplates have a non-uniform spectral-bandwidth requirement. The spectral bandwidth used during data acquisition meets the requirement of the zoneplate for the x-direction (vertical features), but not for the y-direction (horizontal features). The corresponding chromatic blur can be corrected by reducing the spectral bandwidth of the beamline at the expense of flux.

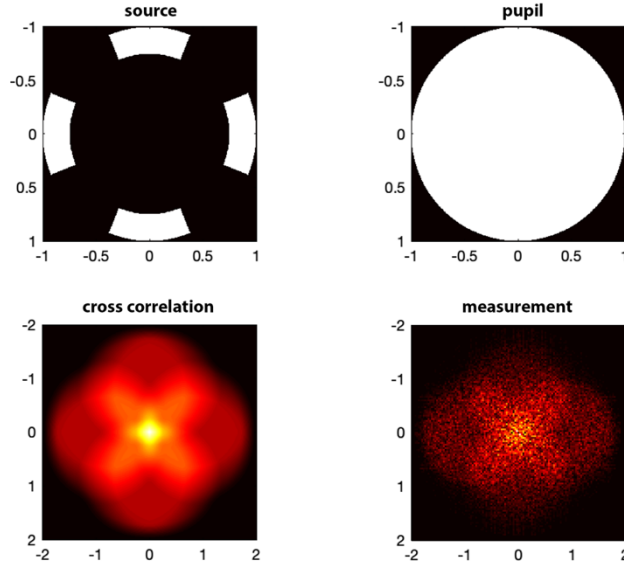


Fig. 6 Partially coherent imaging model: source angular spectrum (quasar illuminator), imaging pupil, cross correlation of the source and pupil, and measured power spectral density (0.33 4xNA zoneplate), corrected for resampling.

Figure 7 shows the cross correlation between the pupil of the 0.55 4xNA/8x zoneplate and a quasar45 illuminator, as well as the measured PSD for this imaging configuration, corrected for resampling. There is again qualitative agreement between the model and measured data. The elliptical aperture and the presence of a central obscuration can be observed in the data. For a given illumination angle, the central obscuration blocks the plus or minus first diffraction order for a range of spatial frequencies. In case the opposite diffraction order falls outside the pupil, the corresponding spatial frequency is not transmitted by the imaging system, causing dark regions within the spectrum. The bright regions along the x and y axes indicate strong modulation in the image for horizontal and vertical features. For the corresponding spatial frequencies, all four poles of the illuminator contribute to the image. The 0.55 4x/8xNA zoneplate has a lower numerical aperture in the y-direction, a reduced chief-ray angle, and shorter working distance. These properties relax the spectral bandwidth requirement of the zoneplate. There is no noticeable chromatic aberration found in the High-NA image data.

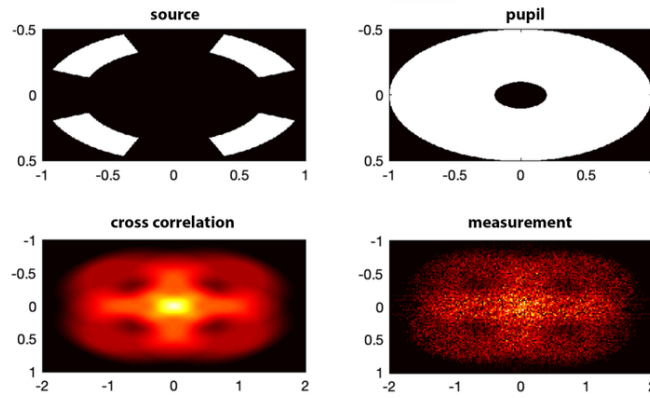


Fig. 7 Partially coherent imaging model: source angular spectrum (anamorphic), imaging pupil (anamorphic, centrally obscured), cross correlation of the source and pupil, and measured power spectral density (0.55 4x/8xNA zoneplate), corrected for resampling.

Figure 8 shows the apparent 1D MTF in x and y for the 0.33 4xNA zoneplate, using a disk illuminator. To compute the data, instead of computing a 2D PSD, 1D PSD data are computed from the image line by line for the two orientations. For a given spatial frequency of the single-line PSD, the variance equals the ensemble-average PSD value at that frequency. The noise in the PSD is reduced by averaging over $N=278$ lines, corresponding to a $3\text{-}\mu\text{m}$ region of interest (ROI). The single-lens imaging system of the SHARP microscope achieves diffraction-limited imaging performance over an area of a few micrometers at the center of the field of view. The useable ROI is limited by field-dependent aberrations. Greater noise reduction in the PSD can be achieved for imaging systems with a larger diffraction-limited field of view.

The averaged PSD data are corrected for the impact of resampling. Piecewise second-order polynomial fitting is used to display monotonous graphs across the noisy data. The actual datapoints are also shown. The nominal apparent MTF for $0.85\text{-}\sigma$ illumination is shown for reference. The data are recorded at a target σ of 0.95. The MTF extracted from the data exceeds the $0.95\text{-}\sigma$ nominal apparent MTF for low spatial frequencies. The high spatial-frequency content is reduced. The shape of the measured MTF curve suggest that the effective σ of the illumination for the corresponding image data is lower than 0.95.

For the most part, the difference between the measured MTF in x and y can be attributed to chromatic aberration, as discussed earlier. The difference in shape between the two curves also suggests a slight difference in effective σ between the two orientations.

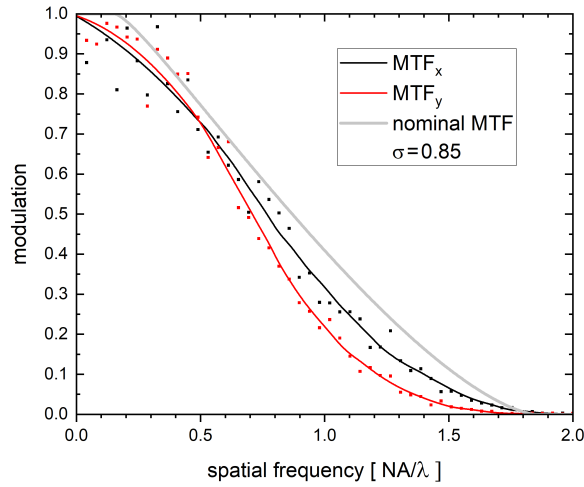


Fig. 8 Apparent 1D modulation transfer function of the 0.33 4xNA zoneplate in x and y, using disk illumination (measured data points, and piecewise second-order polynomial fits), and nominal apparent modulation transfer function of a diffraction-limited imaging system at an illumination σ of 0.85.

5 Summary and Outlook

BPRA targets are an established standard for calibrating and characterizing optical instruments in the frequency domain. This work expands the BPRA standard to applications in EUV imaging. A BPRA target with a smallest feature size of 40 nm is fabricated on a silicon wafer with an EUV multilayer coating. The target uses a 39-nm thick nickel absorber. The target is imaged on the SHARP EUV mask microscope under different imaging conditions. The properties of the imaging system and illumination are imprinted on the corresponding PSD data, including the shape of the aperture, presence of a central obscuration, and the effective source angular spectrum. The obtained PSD data are sensitive to aberrations, misalignment, and inaccuracies in the pupil fill. Extracting the apparent MTF for the corresponding imaging configuration from the PSD data is discussed. A partially-coherent imaging model is presented as a reference to the experimental results. The EUV BPRA target establishes an in-situ and portable calibration and alignment standard for EUV imaging. The smallest feature size of the BPRA target is well-suited for the 0.33NA generation of EUV lithography. The next step is the development of a BPRA target with a smallest feature size of 20 nm to support the coming 0.55NA generation of EUV lithography.

286 *Disclosures*

287 This research may lead to the development of products in which the authors have a business and/or
288 financial interest.

289 *Code, Data, and Materials Availability*

290 Proprietary information will not be made available, but paper content is consistent with SPIE
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Caption List

Fig. 1 Scanning-electron microscopic image, showing a region of the BPRA target with a smallest feature size of 40 nm. The target is patterned using a 39-nm thick nickel absorber on a 4" silicon wafer with a molybdenum/silicon multilayer coating.

Fig. 2 Partially coherent imaging model: source angular spectrum, imaging pupil, cross correlation of the source and pupil, and corresponding apparent modulation transfer function.

Fig. 3 Apparent modulation transfer functions of a partially coherent imaging system with illumination σ values from zero to one.

Fig. 4 Power spectral density of a binary pseudo random array with a smallest feature size of 40 nm, resampled to a projected pixel size of less than 40 nm.

Fig. 5 Linear-scale false-color power spectra of image data of the binary pseudo random array target, imaged on the SHARP EUV microscope, using different zoneplate lenses and pupil fills.

Fig. 6 Partially coherent imaging model: source angular spectrum (quasar illuminator), imaging pupil, cross correlation of the source and pupil, and measured power spectral density (0.33 4xNA zoneplate), corrected for resampling.

Fig. 7 Partially coherent imaging model: source angular spectrum (anamorphic), imaging pupil (anamorphic, centrally obscured), cross correlation of the source and pupil, and measured power spectral density (0.55 4x/8xNA zoneplate), corrected for resampling.

Fig. 8 Apparent 1D modulation transfer function of the 0.33 4xNA zoneplate in x and y, using disk illumination (measured data points, and piecewise second-order polynomial fits), and nominal apparent modulation transfer function of a diffraction-limited imaging system at an illumination σ of 0.85.