Zoneplate-based EUV mask microscope with through-pellicle imaging capability

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Abstract. Mirror-based and zoneplate-based imaging systems are being used in actinic EUV reticle review tools. With regard to zoneplates, a short working distance is advantageous in terms of the required spectral bandwidth, manufacturability, and potentially throughput and imaging performance. Zoneplates therefore typically have a short working distance. The industry has adopted the use of an EUV pellicle to protect the photomask. Imaging photomasks through-pellicle requires a working distance larger than 2.5 mm. A zoneplate-based EUV mask microscope with a 3-mm working distance has been commissioned at beamline 11.3.2 of the Advanced Light Source. Through-pellicle imaging at an exposure time of two seconds is demonstrated. The instrument achieves an image contrast of 95% on large features on a photomask with a Tantalum-based absorber. Imaging down to 45-nm half pitch (mask scale) is demonstrated. A NILS of 2.55 is achieved on 60-nm half-pitch (mask scale) lines and spaces. These results demonstrate that zoneplate-based imaging systems can meet the requirements of an actinic EUV mask review tool in terms of imaging performance and throughput in an instrument compatible with EUV pellicles.

Keywords: EUV, microscope, photomask, mask, reticle, pellicle.

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1 Introduction

Mirror-based imaging systems are undoubtedly well suited for actinic reticle review tools for Extreme Ultraviolet (EUV) lithography. The strict requirements in terms of figure error and surface roughness as well as the required multilayer coatings make these optics expensive and time-consuming to produce. Only a small number of companies have the capability to make such optics. Fresnel zoneplate lenses offer diffraction-limited imaging performance at EUV wavelengths[1]. Zoneplate lenses can be produced relatively fast and at a fraction of the cost of mirror-based imaging systems for EUV. The industry operates both zoneplate-based[2] and mirror-based[3] reticle review tools today.

A zoneplate lens working in transmission consists of a diffractive grating structure nanopatterned on a thin membrane, typically by electron-beam lithography. The larger a zoneplates becomes, the more challenging it can become to produce. Large zoneplates are typically more prone to aberration, more fragile and often less efficient than smaller ones. In addition, zoneplate lenses require monochromatic light. The inverse spectral bandwidth requirement $\lambda/\Delta\lambda$ is approximately equal to the number of zones of the zoneplate N. N scales with the working distance p and the numerical aperture (NA) squared: $N \approx p \cdot NA^2/\lambda$

For these reasons, zoneplate lenses for EUV and soft x-ray wavelengths typically have a working distance below one millimeter. The SHARP EUV microscope[4] has a working distance of 0.5 mm at 0.0825 NA (corresponding to 0.33 NA on the wafer side of a 4x system, hereafter labeled 0.33 4xNA) and the zoneplates have a diameter of 85 µm. To image a photomask with a pellicle installed, a working distance larger than 2.5 mm is required, which is challenging to achieve in a zoneplate-based microscope. At 3-mm working distance, a 0.33 4xNA zoneplate has a diameter of nearly 500 µm and an inverse bandwidth requirement of 1500. A 0.55 4x/8xNA zoneplate at 3-mm working distance is nearly 800 µm by 400 µm in size and has an inverse bandwidth requirement of 4200. The required bandwidth can be achieved with a monochromator, albeit at the expense of flux and hence throughput of the instrument.

2 Overview of the Microscope

A mask microscope using zoneplate lenses with a 3-mm working distance has been commissioned at beamline 11.3.2 of the Advanced Light Source at Lawrence Berkeley National Laboratory. The bending-magnet beamline has a flux of 10^{11} photons/s at 0.01% bandwidth at 100 eV and a spectral resolution of 1/7000. The beamline has two sets of four-jaw slits to control the size of the intermediate focus and the divergence of the beam.

The layout of the microscope is similar to the SHARP microscope. To enable through-pellicle imaging, the working distance is increased to 3 mm. The SHARP microscope works in an off-axis geometry. This configuration increases the inverse bandwidth requirement. In order to reduce the inverse bandwidth requirement at 3 mm of working distance, an on-axis geometry is chosen for the pellicle-compatible microscope. Further details on the optical configurations of the instruments can be found in reference 5.

Figure 1 illustrates the optical layout of the microscope. The beamline intermediate focus is imaged onto a flat scanning micromirror (MEMS) by a spherical condenser mirror at 9x demagnification. An ellipsoidal illuminator mirror images the light from the MEMS mirror onto the photomask, providing critical illumination to the microscope. The illuminator mirror covers the mask-side angular range of the 0.33NA and 0.55NA EUV lithography scanner generations. A flat folding mirror between the MEMS mirror and the illuminator mirror is used to redirect the beam. The illuminator mirror has a demagnification of 3.4x. The combined demagnification between the beamline intermediate focus and the mask plane is close to 30x. The beamline intermediate focus has a size of about 150 µm FWHM and the illuminated spot on the photomask is about 5 µm FWHM. The illuminator mirror is mounted to a scanning stage. Scanning the beam a few microns across the photomask provides uniform illumination over the diffraction-limited imaging region of the microscope. Scanning at larger amplitudes allows to illuminate the full 30-µm by 30-µm field of view during mask navigation and optical alignment.

The focal point on the MEMS mirror and the illuminator focal point in the mask plane are optical conjugates. As such, light from the MEMS mirror is always imaged to the illuminator focal point in the mask plane. The desired pupil fill is created, using the programmable MEMS mirror to scan the low-divergence synchrotron beam across the aperture of the illuminator mirror over the course of the exposure[6]. The MEMS mirror is made by Mirrorcle Technologies. It has a diameter of 1.2 mm and scans the beam at frequencies of up to 1 kHz. The EUV multilayer coating has been added to the mirror at the at the Center for X-Ray Optics. The peak reflectivity of the coating is 49%. A reflectivity above 48% is achieved over a region of 320 µm, which is several times the size of the focused beam on the mirror.

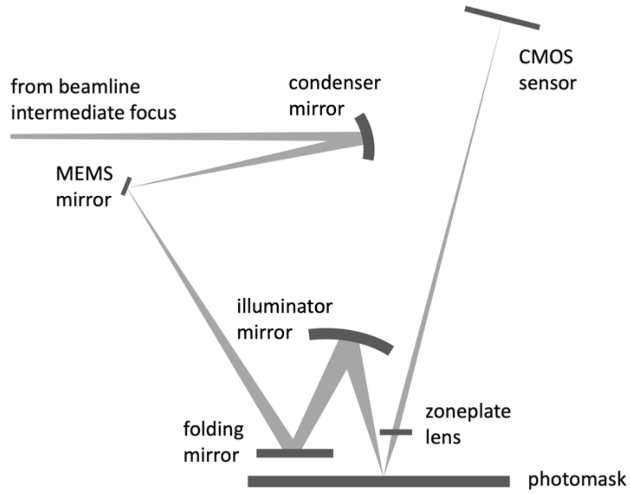

Fig. 1 Optical layout and components of the microscope (not to scale).

A zoneplate lens in an on-axis configuration images the region of interest on the photomask to an Andor Marana X CMOS image sensor with a 6.5-µm pixel size. The photomask is sampled at 15 nm/pixel at a magnification of 433x. The zoneplate holder is designed to hold up to 45 zoneplates on three separate chips. Due to their size, the zoneplate chips are installed parallel to the mask, which leads to a six-degree tilt between the zoneplate aperture and the chief ray. This causes a twelve-degree tilt in the mask-side focal plane of the microscope.[5] The same tilted focal plane is present in the SHARP microscope which also has the zoneplates parallel to the mask. The tilted focal plane can be corrected computationally if desired.

At the center of the field of view, the image is unaberrated. Field-dependent aberrations are present away from the center. Near the center, the aberrations are small. The RMS wavefront error remains below 35 Milliwaves within a 2-µm radius, which is acceptable for most applications. An imaging system can be considered diffraction-limited up to 70 Milliwaves of RMS wavefront error ($\lambda/14$) according to the Maréchal criterion. The nominal field size for the 0.33 4xNA zoneplates is rated at 4 µm by 4 µm at the mask.

The moderate cost and fast production cycle of zoneplate lenses affords the means to include a variety of NA values, aperture shapes and pupil functions in a single instrument[7] and add new capabilities within a few weeks to months. The 0.33 4xNA zoneplate lens used to acquire the image data shown in Section 3 is made by Applied Nanotools. It is patterned in Tungsten on a 50-nm Silicon Carbide membrane.

3 Imaging Results

3.1 Through-Pellicle Imaging

Imaging through the pellicle requires a gap between the zoneplate package and pellicle to prevent damage. The zoneplate package measures approximately 70 mm by 30 mm. By design, the corners of the package are approximately 100 µm lower than the zoneplate chips. A collision between the zoneplate package and the pellicle or frame would therefore occur at one of the corners of the package. At a nominal height of the pellicle and frame of 2.5 mm above the mask, and a working distance of 3 mm, a gap of approximately 0.4 mm remains when the microscope is in focus. Image data is recorded at the center of the mask, on all four quadrants of the mask, and from the alignment fiducials near the corners of the mask with the zoneplate package extending across the pellicle frame. The pellicle remains intact and mechanical interference between the pellicle frame and zoneplate package is not observed during the imaging test. Figure 2 shows an image recorded through the pellicle. The full 30-µm by 30-µm field of view is shown. To capture the image, the illuminator is set to navigation mode where the light from the illuminator mirror is scanned across a larger area to illuminate the entire field of view. The image is recorded at an exposure time of three seconds, using low-sigma annular illumination. The photomask with a pellicle, available at the time of the experiment, does not have small features.

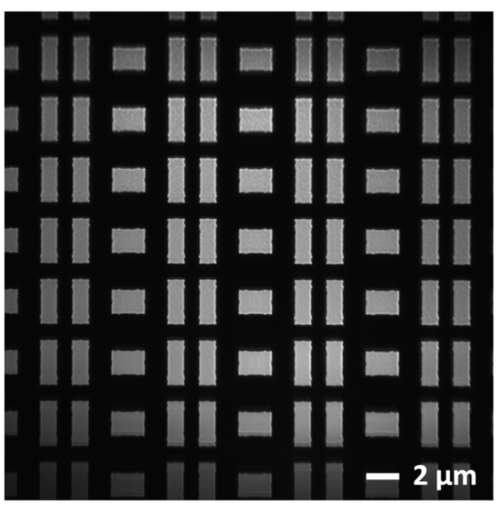

Fig. 2 EUV microscopic image recorded through the pellicle.

3.2 Image Contrast

To evaluate background intensity in the image from flare or other sources, image data is recorded, separating the image into two regions. One half is (mostly) clear multilayer and the other half is absorber. The edge is placed across the plane of incidence. Image data is recorded with the clear region in the upper half of the image as well as the lower half. Data is recorded through-pellicle near the center of the mask and at a fiducial near the upper left corner of the mask, outside the pellicle. A photomask with a Tantalum-based absorber is used. The image contrast is 95% in all four images. Figure 3 (a) shows the four images. The full field of view of the microscope is shown. Here, the illuminator is set to imaging mode where the light is concentrated on the diffraction-limited imaging region within the field of view. Some scanning of the illuminator mirror is applied to increase uniformity across the 4-µm by 4-µm (mask scale, 4x) imaging region. The images are recorded at a two-second exposure time, using annular illumination with an inner sigma of 0.3 and an outer sigma of 0.8. Depending on the illumination settings, the microscope exposes the image sensor to its full-well capacity of 55k electrons per pixel in less than three seconds on large features. Figure 3b shows cross-section plots of the image data, averaged over 20 lines.

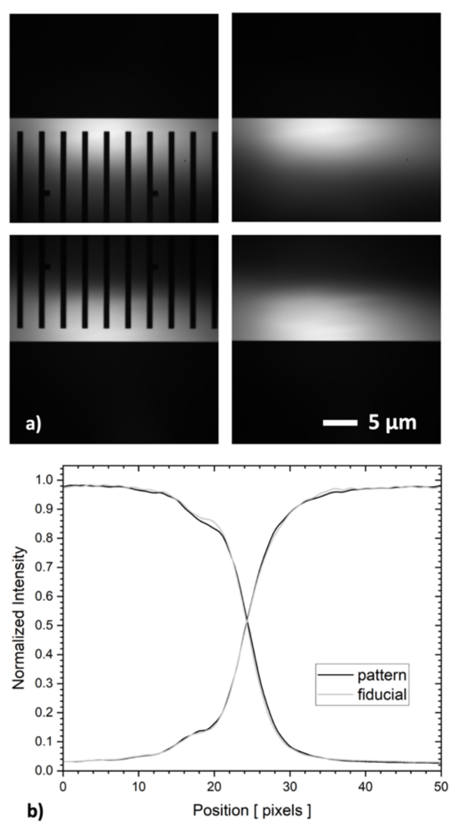

Fig. 3 (a) Images of a horizantal edge, recorded through-pellicle, near the center of the mask (left), and near the upper left corner of the mask (right), outside the pellicle, and (b) cross section plots of the image data.

3.3 NILS and Modulation

To evaluate the imaging performance of the microscope, image data of lines and spaces is recorded on a second photomask with a Tantalum-based absorber, which does not have a pellicle. Figure 4 shows horizontal and vertical image data of lines and spaces with 45 nm, 50 nm, and 60 nm half pitch (mask scale, 4x). The 4-µm by 4-µm diffraction-limited imaging region is shown.

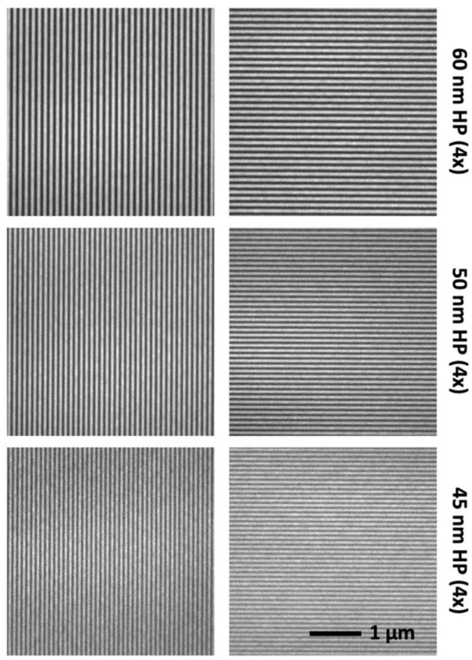

Fig. 4 Image data of vertical and horizontal lines and spaces.

The images are recorded at a three-second exposure time, using leaf-dipole illumination at an outer sigma of one. For the 50-nm and 60-nm half-pitch (4x) lines, the pole offset delta sigma[8] is 1.76. For the 45-nm half-pitch (4x) lines, an offset of 1.86 is used. The nominal pupil fill ratio (PFR) for these fills is quite aggressive at approximately 10% and 5% respectively. However, due to the divergence of the beam reflecting off the MEMS mirror, the effective PFR is larger. It is estimated to be about 15% for the larger pole size and about 10% for the smaller pole size. The four-jaw slits at the beamline can be used to decrease the divergence of the beam and thus, increase pupil resolution at the expense of flux.

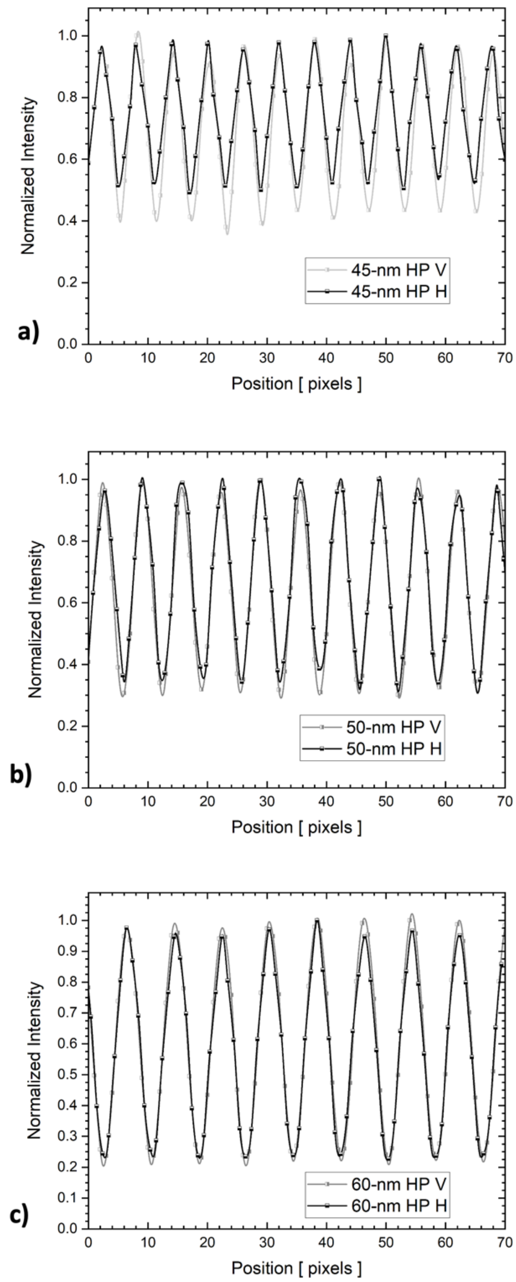

Fig. 5 Line profiles of the image data from Figure 4.

Figure 5 shows line profiles of the image data from Figure 4. The cross sections are 70 pixels (~1000 nm) wide and are averaged over 10 pixels along the pattern direction. For small pitches, modulation in the image is affected by the placement of the lines relative to the pixel array of the image sensor. Reducing the mask area per pixel in the image through increased magnification or a smaller pixel size would improve the imaging performance of the microscope for small pitches at 0.33 4xNA and at 0.55 4xNA (on vertical features). When imaging photomasks without a pellicle, an increased magnification can easily be achieved using a zoneplate lens with a reduced working distance. At a given NA, decreasing the working distance reduces the size of the zoneplate and the number of zones, which allows to increase the spectral bandwidth and throughput of the microscope.

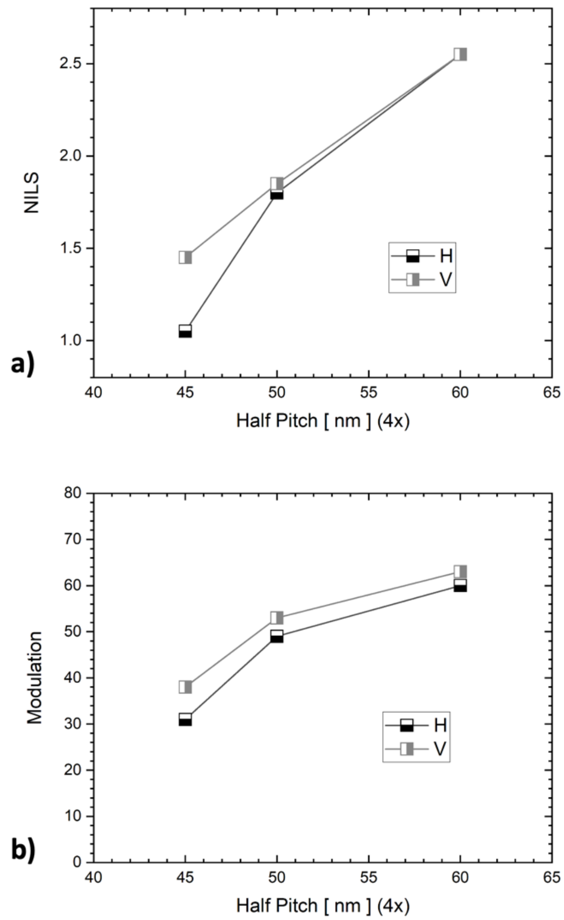

Fig. 6 (a) NILS, and (b) modulation of the image data from Figure 4.

NILS and modulation values, obtained from the image data presented in Figure 4, are given in Figure 6. At 45-nm half pitch (4x), near the resolution limit of the 0.33 4xNA zoneplate, a modulation of 38% is achieved on the vertical lines. For the horizontal lines, the modulation is 31%. Shadowing along the plane of incidence and mask 3D effects contribute to the observed reduction in modulation on horizontal features. The relative loss in modulation decreases towards larger pitches. At 50-nm half pitch (4x), the modulation is 53% for vertical lines and 49% for horizontal lines. The corresponding NILS values are 1.85 in the vertical orientation and 1.8 in the horizontal orientation. At 60-nm half pitch (4x), a NILS of 2.55 is achieved both for horizontal and vertical lines.

The transmission of the pellicle is approximately 90% on a single pass, reducing the brightness of the image. The pellicle is designed to shield the photomask from particles without further affecting the image. The data presented in section 3.2 does not show any impact of the pellicle on the image. NILS and modulation values for the feature sizes discussed in this section are expected to be similar on a photomask with a pellicle installed.

4 Conclusion

A zoneplate-based EUV mask microscope with through-pellicle imaging capability has been commissioned at beamline 11.3.2 of the Advanced Light Source. The 3-mm working distance of the microscope ensures a gap of approximately 400-µm between the zoneplate package and the pellicle at all times, thus preventing damage to the pellicle. Imaging through-pellicle at an exposure time of two seconds has been demonstrated on all four quadrants of the mask. The instrument achieves an image contrast of 95% on large features on a photomask with a Tantalum-based absorber. Imaging down to 45-nm half pitch (mask scale) is demonstrated. A NILS of 2.55 is achieved on 60-nm half-pitch (mask scale) lines and spaces. Exposure time and imaging performance are comparable to the SHARP EUV mask microscope. These results clearly demonstrate that zoneplate-based microscopes with pellicle-capability can meet the requirements of an actinic EUV reticle review tool both in terms of imaging performance and throughput.

Code, Data, and Materials Availability

Company proprietary information will not be made available, but manuscript content is consistent with JM3 technical content guidelines.

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