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Invited Paper

Overview and Status of the 0.5-NA Micro-field Exposure Tool at Berkeley Lab

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ABSTRACT

A 0.5-NA extreme ultraviolet micro-field exposure tool has been installed and commissioned at beamline 12.0.1.4 of the Advanced Light Source synchrotron facility at Lawrence Berkeley National Laboratory. Commissioning has demonstrated a patterning resolution of 13 nm half-pitch with annular 0.35 – 0.55 illumination; a patterning resolution of 8 nm half-pitch with annular 0.1 – 0.2 illumination; critical dimension (CD) uniformity of 0.7 nm 1σ on 16 nm nominal CD across 80% of the 200 um x 30 um aberration corrected field of view; aerial image vibration relative to the wafer of 0.75 nn RMS and focus control and focus stepping better than 15 nm.

1. INTRODUCTION

To meet industry demand for extreme ultraviolet (EUV) materials testing capabilities down to the 2 nm lithography node, the EUV Photoresist Testing Center at Berkeley Lab has been expanded to include 0.5-NA EUV microfield exposure tool with a resolution of 8 nm and robotic sample processing tailed for research. This paper provides an overview of the status, performance, and capabilities of the exposure system as of March 1, 2019. The exposure system will be referred to as MET5 throughout this paper.

2. RESOLUTION

Figure 1 shows the contrast of vertical 1:1 lines as a function of half-pitch in MET5 with annular 0.35 – 0.55 illumination, modeled with Hyperlith [1] configured as shown in Table 1. Figure 2 shows top-down scanning electron microscope (SEM) [2] images of 1:1 vertical lines printed in resist using MET5 with imaging conditions shown in Table 1 and material / processing conditions shown in Table 2. Printing performance tracks expectations based on the contrast of the aerial image; e.g., patterning failure is expected when the contrast of the aerial image drops below 60%, which occurs at a half-pitch of 12 nm.

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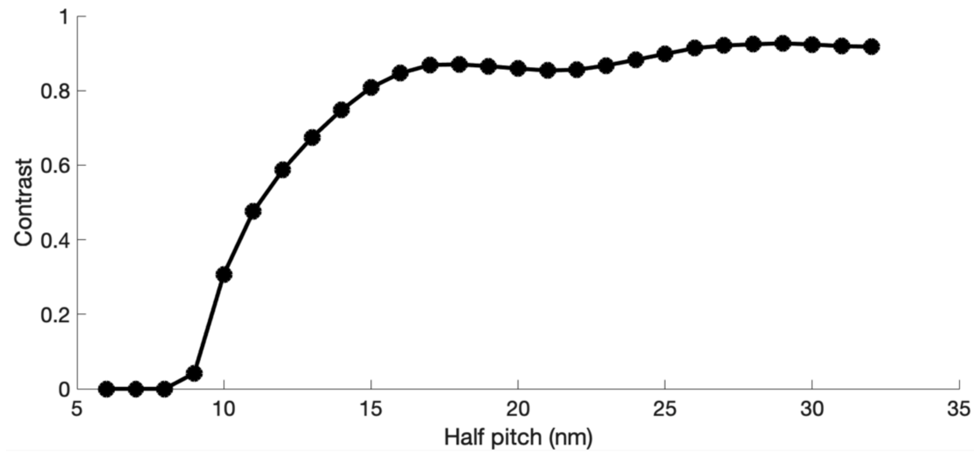

Figure 1: Contrast of 1:1 vertical lines as a function of half-pitch in MET5 with annular 0.35 – 0.55 illumination, modeled with Hyperlith configured as shown in Table 1

Table 1: Configuration of Hyperlith lithography simulation software for calculating the aerial images of 1:1 vertical lines in MET5 with annular 0.35 – 0.55 illumination

Mask	Multilayer	Mo/Si; d-spacing = 6.95 nm; gamma = 0.4; capping = 2 nm Ru
	Absorber	55 nm of TaN topped with 7 nm of TaON (a DUV antireflection coating)
	Optical Proximity Correction	None
Illumination	Wavelength	13.5 nm
	Polarization	Linear X
	Pupil Fill	Annular 0.35 – 0.55
Projection Optics	NA	0.5
	Central Stop	Sigma = 0.3
	Aberrations	0.29 nm RMS as measured with in-situ Lateral Shearing Interferometer
Field Point		Central

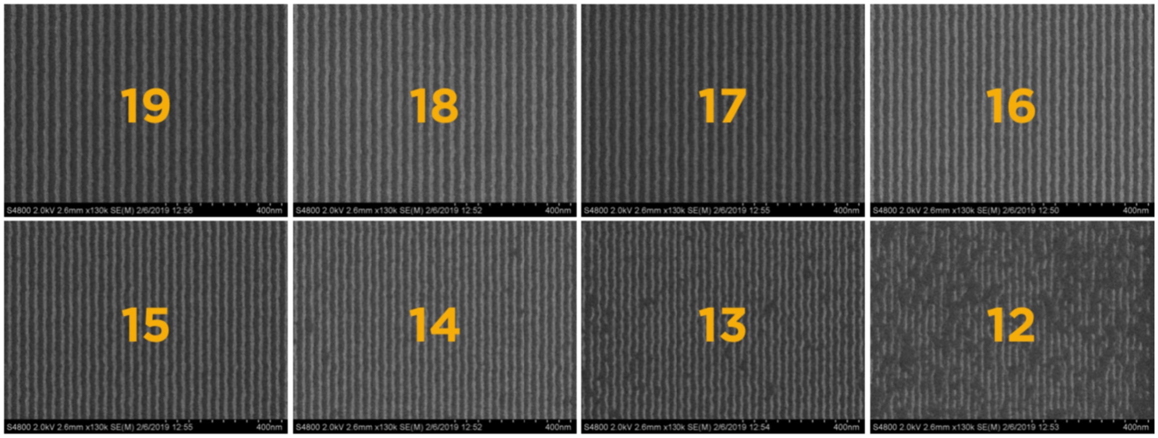

Figure 2: Top-down scanning electron microscope SEM images of 1:1 vertical lines printed in resist using MET5 with imaging conditions shown in Table 1 and photoresist / processing conditions shown in Table 2. Numbers are coded half-pitch

Enhanced imaging for 1:1 lines between 8 nm half-pitch and 15 nm half-pitch is possible with annular 0.1 – 0.2 illumination. When using this illumination, the zero-order light reflected from the reticle is blocked by the central stop of the projection optic and frequency doubling occurs in the image. Figure 3 shows the contrast of frequency-doubled horizontal 1:1 lines as a function of half-pitch in MET5 with annular 0.1 – 0.2 illumination, modeled with Hyperlith configured as shown in Table 2 with the exception of annular 0.1 - 0.2 illumination. Figure 4 shows top-down SEM images of vertical 1:1 lines in resist printed using MET5 with imaging conditions shown in Table 1 and material / processing conditions shown in Table 2. Printing performance tracks expectations based on the contrast of the aerial image. For 9 nm half-pitch and 8 nm half-pitch, additional work is required to demonstrate fully resolved patterning. Metrology of these features is nearing the performance limit of the SEM used for metrology. It is difficult to judge from the images if the resist is fully resolved to the Si substrate or if the resist is a bulk block with sinusoidal thickness modulation.

Table 2: Photoresist and processing conditions used for all exposures in MET5

Substrate	Si
Resist	Inpria YATU series MOx
Thickness	20 nm
Spin Speed	1500 RPM 45 sec
Post Application Bake	100 C / 120 sec
Post Exposure Bake	170 C / 120 sec
Hard Bake	200 C / 300 sec

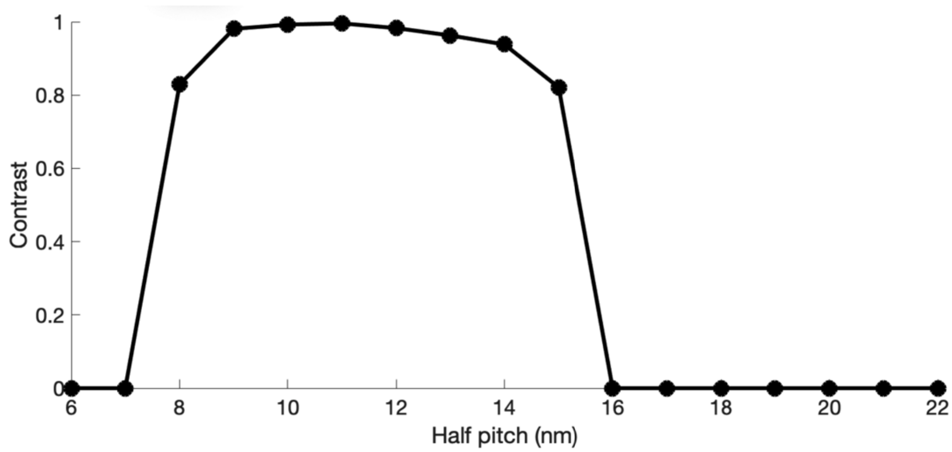

Figure 3: Contrast of frequency-doubled horizontal 1:1 lines as a function of half-pitch in MET5 with annular 0.1 – 0.2 illumination, modeled with Hyperlith configured as shown in Table 3

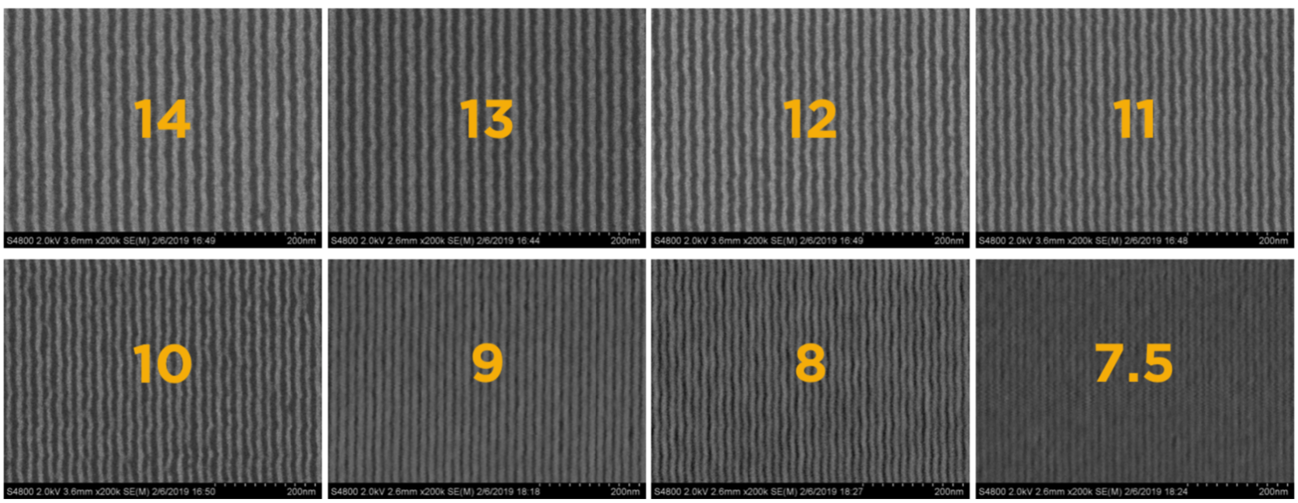

Figure 4: Top-down scanning electron microscope SEM images of 1:1 vertical lines in MET5 with imaging conditions shown in Table 1 and photoresist / processing conditions shown in Table 2. Numbers are coded half-pitch

3. ASTIGMATISM

Figure 5 (left) shows a top-down SEM image of a 16 nm 1:1 astigmatism target. The astigmatism target contains 16 nm half-pitch 1:1 dense lines at orientations of 0°, 90°, 45°, and -45°. 16 nm half-pitch astigmatism targets were printed with 0.35 – 0.55 annular illumination at defocus values of -75 nm, -60 nm, -45 nm, -30 nm, -15 nm, 0 nm, 15 nm, 30 nm, 45 nm, 60 nm, and 75 nm. Top-down SEM images, similar to the SEM image in Figure 5 (left), were obtained for each exposure in the through-focus series. Commercial SEM image analysis software was used to calculate the average line width roughness (LWR) of the 1:1 line blocks at orientations of 0°, 90°, 45°, and -45° in each SEM image. Figure 5 (right) shows LWR vs. defocus for each orientation. Quadratic best fits to each experimental data set were not obtained; however, bye eye, all four orientations have LWR minimized within a 30 nm defocus range, which is less than the depth of focus of the exposure system.

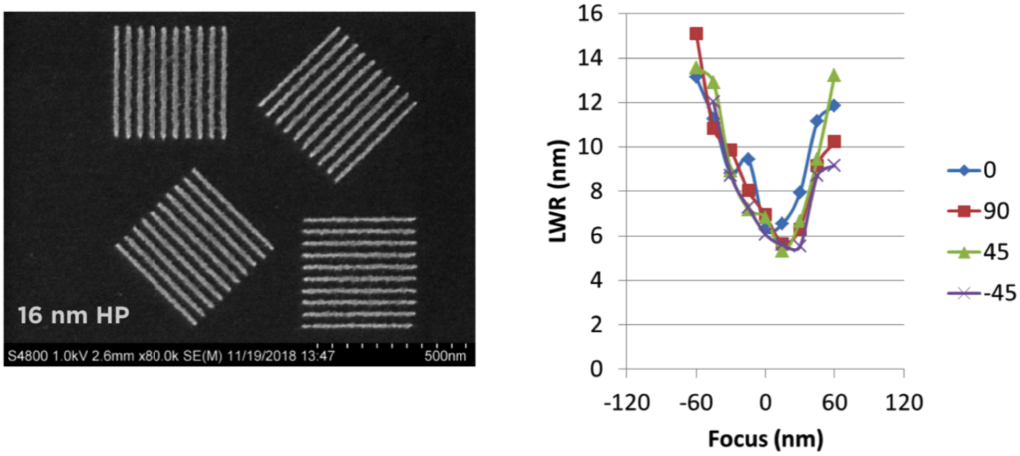

Figure 5: (Left) top-down SEM image of a 16 nm 1:1 astigmatism target. The astigmatism target contains 16 nm half-pitch 1:1 dense lines in four orientations: 0°, 90°, 45°, and -45°. (Right) Measured LWR vs. defocus at orientations of 0°, 90°, 45°, and -45°.

4. FOCUS CONTROL

A focus-exposure matrix (FEM) with relative dose values of 1.08^{-2}, 1.08^{-1}, 1, 1.08, and 1.08^{2} and defocus values of [-45 nm, -30 nm, -15 nm, 0 nm, 15 nm, 30 nm, and 45 nm] was exposed on a single wafer using 0.4 – 0.8 annular illumination and material / processing conditions shown in Table 2. Top-down SEM images of 14 nm 1:1 vertical lines were captured at the same site of each exposure. Commercial SEM image analysis software was used to calculate the average critical dimension (CD) of the printed lines in each exposure. Figure 6 (left) shows the average CD vs. defocus curve for each relative dose (1.08^{-2}, 1.08^{-1}, 1, 1.08, and 1.08^{2}). These curves are known as Bossung curves. Each curve is smooth and quadratic and the minimum of each curve falls within the depth of focus of the exposure system (shown in gray. These data demonstrate the ability to set defocus as desired at each unique (x, y) exposure site of the FEM. Figure 6 (right) shows similar data for a different FEM with dose values of 1.2^{-1}, 1, and 1.2.

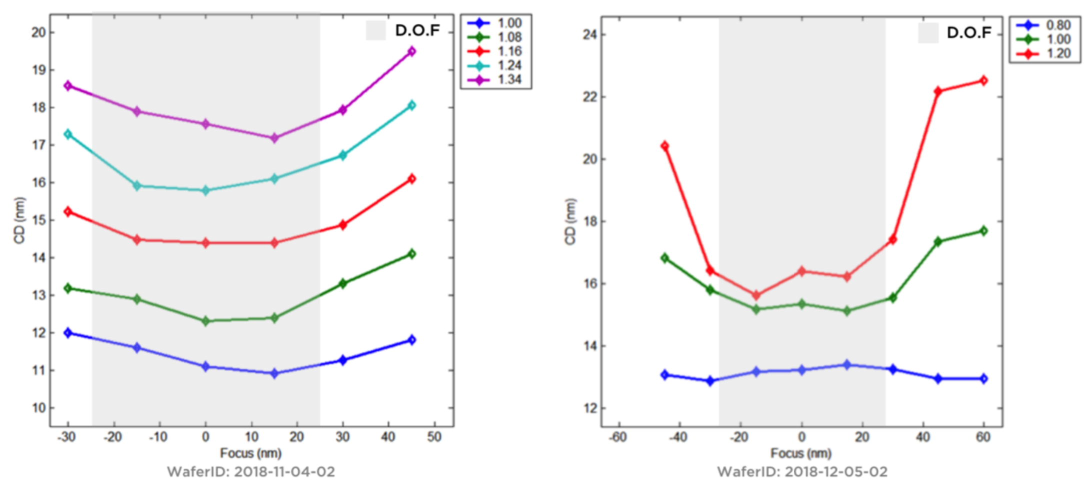

Figure 6: (Left) Bossung curves for 14 nm 1:1 vertical lines (nominal) in MET5 with annular 40-80 illumination. (Right) Bossung curves for 15 nm 1:1 vertical lines (nominal) in MET5 with annular 40-80 illumination.

5. CD UNIFORMITY ACROSS THE FIELD

Figure 7 shows a top-down SEM image of the entire 200 um x 30 um field of MET5. In this exposure, the field contains a 3 x 5 matrix of identical subfields. Top-down SEM images of 16 nm 1:1 vertical lines within each subfield were captured. The approximate locations of the replicated 16 nm 1:1 vertical line features across the field are outlined in Figure 7. Commercial SEM image analysis software was used to calculate the average CD of the printed lines at each subfield. Table 4 shows the average CD of 16 nm 1:1 vertical lines in each subfield. The average CD of the four left columns of the field 15.9 nm; the standard deviation of the average CD of the four left columns of the field is 0.7 nm. The right column of the field was dosed lower due to an offset of the illumination relative to the field that will be fixed in the future.

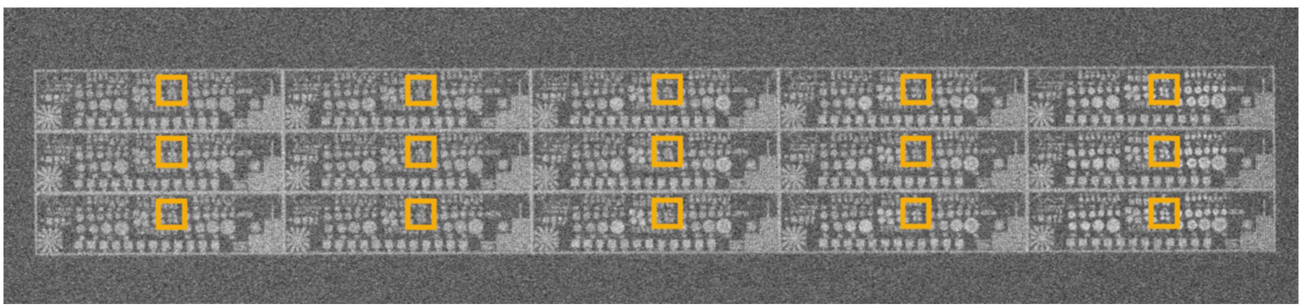

Figure 7: Top-down SEM image of the entire 200 um x 30 um field of MET5. In this exposure, the field contains a 3 x 5 matrix of identical subfields. The approximate locations of the replicated 16 nm 1:1 vertical line features across the field are outlined.

Table 4: The average CD of 16 nm 1:1 vertical lines in each subfield in nm. The average CD of the four left columns of the field 15.9 nm; the standard deviation of the average CD of the four left columns of the field is 0.7 nm

16.9	15.9	14.8	15.2	10.5
17.1	16.5	15.2	15.6	9.5
16.6	16.3	15.7	16.0	10.8

6. AERIAL IMAGE VIBRATION

MET5 is equipped with a displacement measuring interferometer (DMI) that measures the lateral displacements of the mask and wafer relative to the projection optic at 1 kHz with a resolution of 0.1 nm. Figure 8 (top) shows the position of the wafer (x and y) and the reticle (x and y) during a typical image acquisition period of five seconds. Figure 8 (middle) shows the power spectral density (PSD) of the position signals. Figure 8 (bottom) shows the cumulative amplitude spectrum of the position signals, (the integral of the PSD) and shows the accumulated root mean square (RMS) of the position signal up to a specific frequency. The curves labeled “drift x” and “drift y” are the motion of the aerial image relative to the wafer. Drift x and drift y are computed as x_wafer + x_ret/5 and y_wafer + y_ret/5, respectively. E.g., if the wafer moves 1 nm in x at constant velocity over one second and the reticle moves -5 nm in x at constant velocity over 1 one second, the aerial image stays fixed relative to the wafer. The RMS of the drift x and drift y are each about 0.75 nm RMS; about 1/10 the resolution limit of the projection optic.

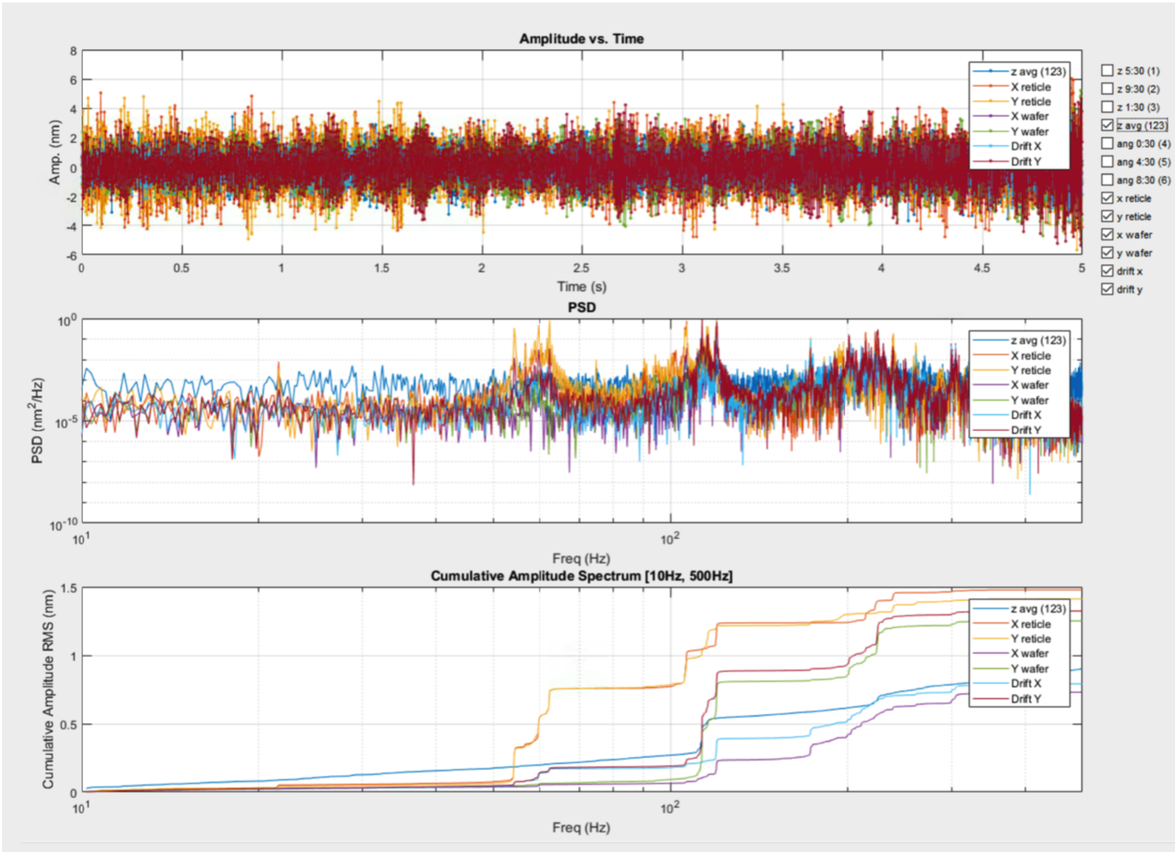

Figure 8: (top) Position of the wafer (x and y) and the reticle (x and y) during a typical image acquisition period of five seconds; (middle) corresponding power spectral density (PSD); (bottom) the corresponding cumulative amplitude spectrum, which is the integral of the PSD and represents the accumulated root mean square (RMS) of the position signal up to a specific frequency.

7. FREE FORM PUPIL FILL

MET5 is capable of free form pupil shaping for imaging at optimal contrast for all feature types. The illuminator of MET5 supports standard pupil shapes including annular, dipole, quadrupole, quasar, and hexapole. It also supports gray scale pupil shapes and complex shapes used for source mask optimization schemes. Figure 9 shows several standard pupil shapes in MET5 obtained from a YAG scintillator placed 10 mm below focus that is imaged trough a port of the vacuum chamber to a CCD camera in air. Some vignetting in that imaging relay occurs.

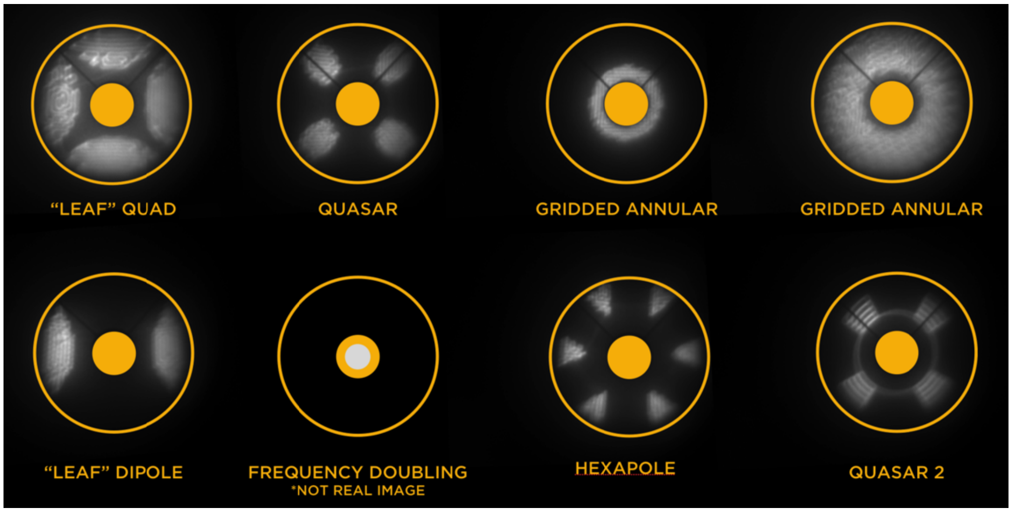

Figure 9: Images of several pupil shapes in MET5 obtained from a YAG scintillator placed 10 mm below focus that is imaged trough a port of the vacuum chamber to a CCD camera in air.

8. SUMMARY

A 0.5-NA EUV micro-field exposure tool has been installed and commissioned at beamline 12.0.1.4 of the Advanced Light Source synchrotron at Lawrence Berkeley National Laboratory. Commissioning has demonstrated a patterning resolution of 13 nm half-pitch with annular 0.35 – 0.55 illumination; a patterning resolution of 8 nm half-pitch with annular 0.1 – 0.2 illumination; critical dimension (CD) uniformity of 0.7 nm 1σ on 16 nm nominal CD across 80% of the 200 um x 30 um aberration corrected field of view; aerial image vibration relative to the wafer of 0.75 nm RMS and focus control and focus stepping better than 15 nm.

This work was performed at Lawrence Berkeley National Laboratory with support from Intel, Samsung, EUV Tech, Inpria, and JSR through the U.S. Department of Energy under Contract No. DE-AC02-05CH11231. Support for the projection optics was also provided by the Department of Energy, Advanced Manufacturing Office.

REFERENCES

[1] http://www.panoramictech.com/index.php?option=com_content&view=article&id=11&Itemid=7
[2] Hitachi S4800 analytical SEM configured with an acceleration voltage of 2keV and an emission current of 5 uA.