Title

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Publication Date

2020

DOI

10.1117/12.2552125

Peer reviewed

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Event: SPIE Advanced Lithography, 2020, San Jose, California, United States

How We Are Making The 0.5-NA Berkeley Micro-field Exposure Tool Stable and Productive

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ABSTRACT

Vibration levels in MET5 exposures were reduced from 1.5 nm RMS to 0.8 nm RMS by tuning the vibration isolation system and removing non-compliant hardware. Frequency doubling exposures were improved by replacing the Fourier-synthesis pupil scanner mirror. Focus-exposure-matrix outliers have been solved by patching a bug in the control software. 9 nm half-pitch lines and 8 nm half-pitch lines were printed in 11 nm thick MOx resist.

Keywords: EUV, High-NA, MET, Microfield Exposure Tool, Photoresist, Berkeley Lab, LBNL, CXRO

1. FIXING BROKEN FREQUENCY DOUBLING IMAGING

In MET5, enhanced imaging for 1:1 lines between 8 nm half-pitch and 15 nm half-pitch is possible with disk 0.0 – 0.1 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 1 shows the contrast of frequency-doubled horizontal 1:1 lines as a function of half-pitch in MET5 with disk 0.0 – 0.1 illumination, modeled with Hyperlith configured as shown in Table 1. Figure 2 shows top-down SEM images of vertical 1:1 lines in resist printed in December 2018, using MET5 with imaging conditions shown in Table 1 and material / processing conditions shown in Table 2.

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	Disk 0.0-0.1
Projection Optics	NA	0.5
	Central Stop	Sigma = 0.3
	Aberrations	0.29 nm RMS as measured with in-situ Lateral Shearing

Extreme Ultraviolet (EUV) Lithography XI, edited by Nelson M. Felix,
Anna Lio, Proc. of SPIE Vol. 11323, 113230B · © 2020 SPIE
CCC code: 0277-786X/20/$21 · doi: 10.1117/12.2552125

		Interferometer
Field Point		Central

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	150 C / 300 sec

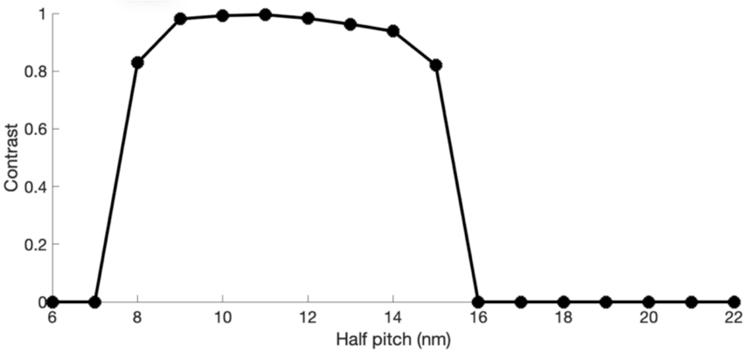


Figure 1: Contrast of frequency-doubled horizontal 1:1 lines as a function of half-pitch in MET5 with annular 0.1 – 0.2 illumination, modeled with Hyperlith configured as shown in Table 3

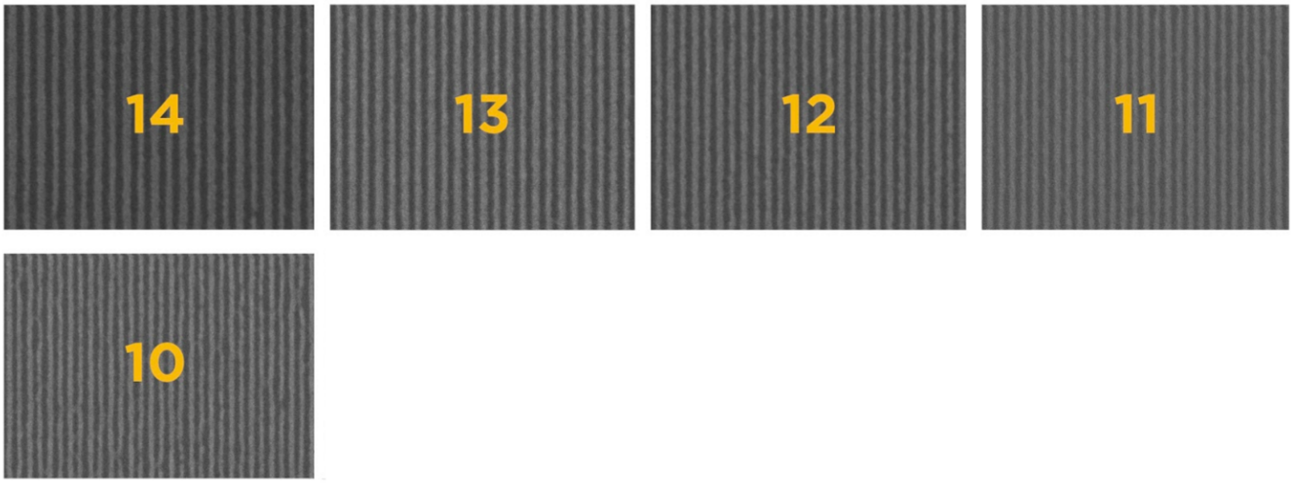


Figure 2: Top-down scanning electron microscope SEM images of 1:1 vertical lines in MET5 with imaging conditions shown in Table 1 and photoresist / processing conditions shown in Table 2. Numbers are coded half-pitch

The lines shown in Figure 2 have alternating widths; this is not normal or expected. For most of 2019, frequency doubling exposures in MET5 looked like this. In September 2019, it was discovered that this effect was caused by scatter from the Fourier-synthesis pupil fill scanner mirror in the illuminator of MET5. Figure 3 left shows the point spread function of the original pupil fill scanner mirror measured in-situ in September 2019; Figure 3 right shows the encircled energy vs. pupil sigma. Due to the in-situ nature of this measurement scatter outside of the pupil of the projection optic could not be measured.

Total integrated scatter[1] (TIS) is defined as the ratio of the diffuse reflected power to the total reflected power (specular + diffuse).

Eq 1. $TIS = 1 - \exp(-(4\pi \cos\theta\ \sigma/\lambda)^2)$

Where:

- σ is the root-mean-square (rms) of the surface error
- surface error is the difference between the measured surface and the ideal design surface
- θ is the angle of incidence from normal

Defining TIS as all energy that lies outside sigma of 0.05, the original pupil scanner mirror had a TIS of about 75%. This value of TIS is created by a surface roughness of about 1.1 nm RMS according to Eq. 1. The surface roughness of the spare pupil fill mirror was measured using a Zygo New View white light interferometric microscope; it was 0.8 nm RMS. Figure 4 shows the modeled aerial image assuming nominal disk illumination of 0.0 – 0.15 with the measured pupil scatter included; alternating line intensity is present.

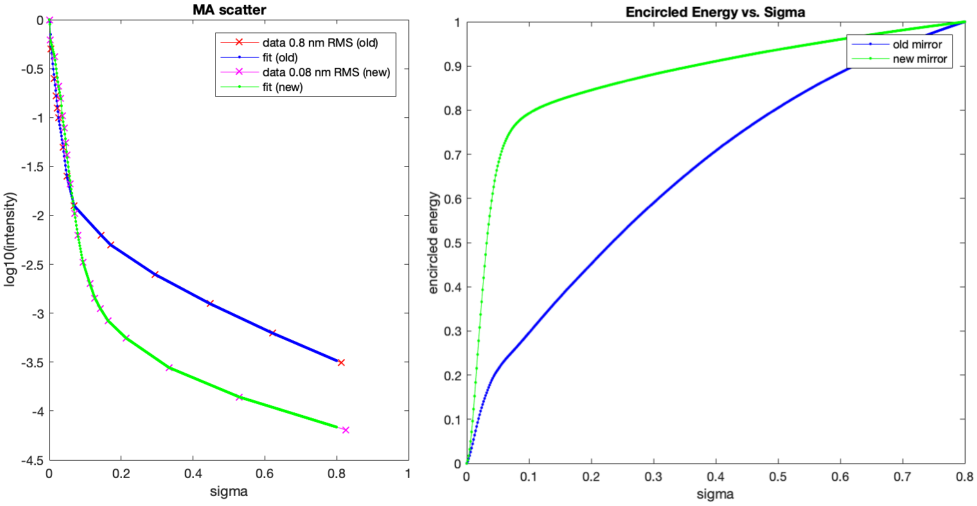
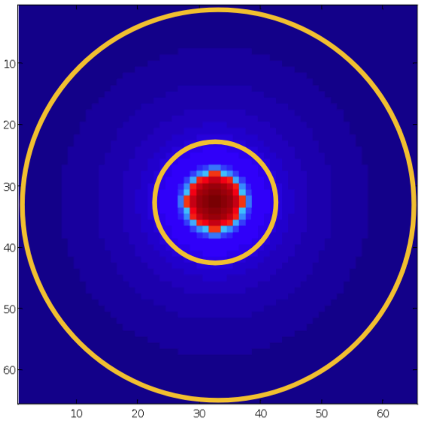
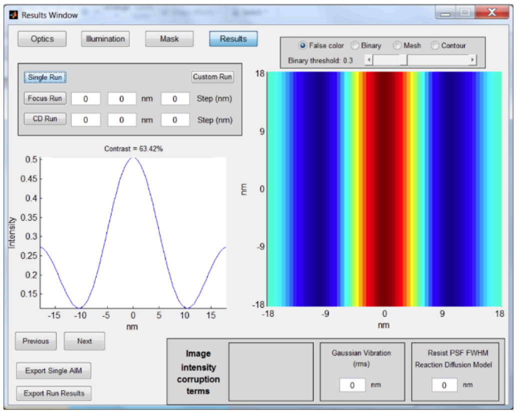


Figure 3: (Left) point spread function of the pupil scanner mirror in MET5. (Right) Encircled energy of the pupil scanner mirror vs. pupil sigma. Blue is the old mirror, and green is the new mirror, installed December 2019.





● False color ○ Binary ○ Mesh ○ Contour

Binary threshold: 0.3

Focus Run 0 0 nm 0 Step (nm)

CD Run 0 0 nm 0 Step (nm)

Contrast = 63.42%

Image intensity corruption terms

Gaussian Vibration (rms) 0 nm

Resist PSF FWHM Reaction Diffusion Model 0 nm

Figure 4: (Left) disk illumination of 0.0 – 0.15 with measured pupil scatter included. The outer yellow ring is the outside edge of the pupil (sigma = 1). The inner yellow ring is the outside edge of the central obscuration (sigma = 0.3) (Right) modeled aerial image assuming nominal disk illumination of 0.0 – 0.15 with the measured pupil scatter included; alternating line intensity is present.

In December 2019, the pupil scanner mirror was replaced with smoother part that had a surface roughness of 0.08 nm RMS (one tenth the roughness of the original part). The point spread function of the replacement pupil fill scanner mirror was measured in-situ after the replacement. The data is shown in Figure 3 (green). The new part has about one tenth of the scatter intensity and superior encircled energy. Figure 5 shows top-down SEM images of horizontal 13 nm half-pitch lines in resist printed in December 2019 with imaging conditions shown in Table 1 and material / processing conditions shown in Table 2 with the original pupil scanner mirror (left) and replacement pupil scanner mirror (right). The alternating line artifact with the original pupil scanner can be intuited as overlaying a non-frequency doubled image generated by the background scattered pupil fill with the desired frequency-doubled image.

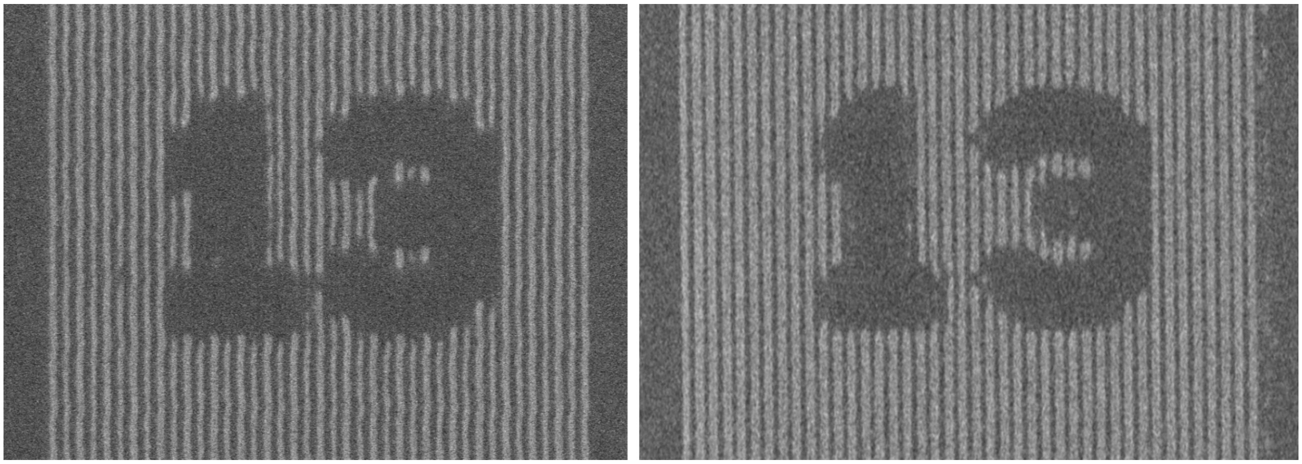


Figure 5: Top-down SEM images of horizontal 13 nm half-pitch lines in resist printed in December 2019, using MET5 with imaging conditions shown in Table 1 and material / processing conditions shown in Table 2 with the original pupil scanner mirror (left) and replacement pupil scanner mirror (right).

2. REDUCING VIBRATION

Figure 6 shows the vibration isolation system (VIS) of MET5. The VIS is built around 4ea vacuum compatible MinusK[2] SM-1 passive isolators. The isolators frequency is 1 Hz vertical, 0.5 Hz lateral. For maximum performance, the center of gravity of the isolated payload, or subframe, is coincident with wafer and in the plane defined by the top of the isolators.

Because of the compliance of the system, the isolators were retrofitted with motorized levelers and encoders, in order to keep the payload level when the large masses of the reticle stage assembly and wafer stage assembly shift around.

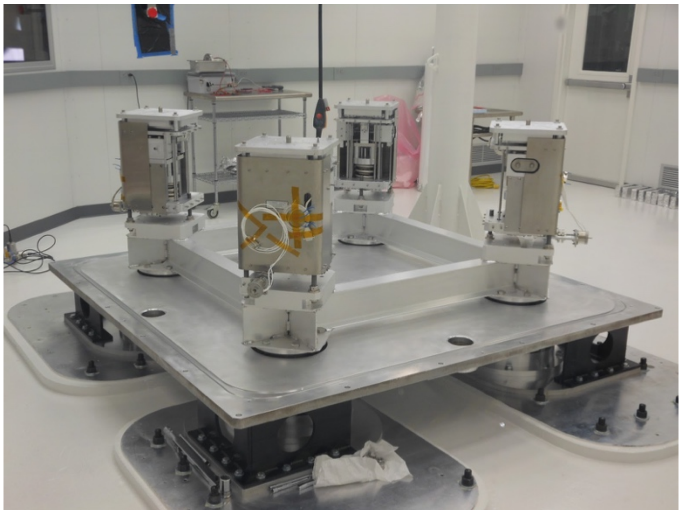


Figure 6: The vibration isolation system of MET5 is built around 4ea vacuum compatible MinusK SM-1 passive isolators.

MET5 is equipped with displacement measurement interferometers (DMIs) that can measure the transverse position of the reticle and the wafer with a resolution of 0.1 nm at 1 kHz. For most of 2019, typical vibration levels during exposures were 1.6 nm RMS or higher.

2.1 Tuning the Vibration Isolation System

In September 2019, during a routine piston of the isolated payload, the VIS was found to be in an imbalanced configuration, with two of the four isolators supporting the majority of the payload. It is believed the system was in this configuration since commissioning. In September 2019, the spring tensions of the isolators were adjusted to redistribute the mass of the payload evenly between the isolators. After rebalancing, vibration levels during exposures were reduced to about 1.0 nm RMS.

2.2 Identifying and Removing Non-Compliant Hardware from the Isolated Payload

In November 2019, non-compliant hardware on the isolated payload was identified. The assembly consisted of 4ea motor, clutch and mounting bracket that connect to the spring tensioner of each vibration isolator. As shown in Figure 7, the assembly contains two heavy masses (motor + clutch) on a long lever arm that is unconstrained. This assembly is on the isolated side of the VIS and is driven vertically at 1 Hz, the natural resonance of the VIS.

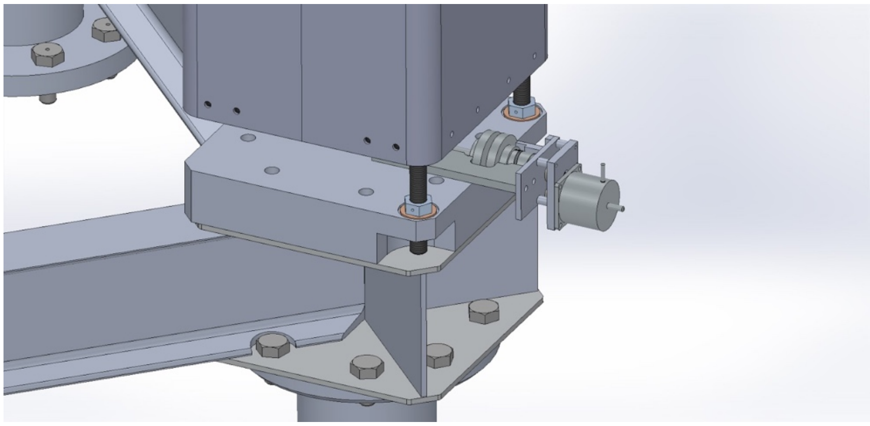


Figure 7: 4ea motor, clutch and mounting bracket that connect to the spring tensioner of each vibration isolator

In December 2019, 4ea motors and clutches were removed. After removal, vibration levels dropped to about 0.6 nm RMS. Vibration levels have fluctuated between about 0.5 nm RMS and 0.8 nm RMS since December 2019 when the system is at rest. In use, vibrations levels increase due to mechanical energy from stage motion exciting natural resonances of the subframe. In February 2020, the control software was improved with a vibration settling routine that waits for vibration to settle to a desired value before every exposure. Figure 8 shows a vibration log from a focus exposure matrix showing the vibration of every exposure is less than the target level of 1.0 nm RMS.

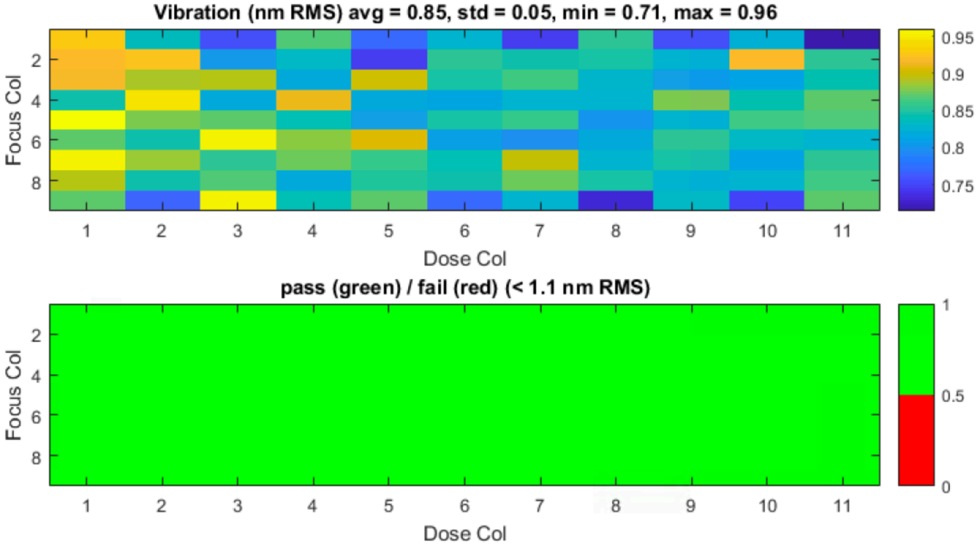


Figure 8: vibration log from a focus exposure matrix showing the vibration of every exposure on the wafer is less than the target level of 1.0 nm RMS.

3. FIXING OUTLIERS IN THE FOCUS EXPOSURE MATRIX

In November 2019, a bug with the MET5 control software was identified. The bug allowed the wafer stage to move to the next exposure site of the focus exposure matrix (FEM) before the shutter was closed from the previous exposure, in certain situations. Exposure times > 5 seconds were the most likely to be affected. This was a bug for the entire history of MET5. The bug occurred because the FEM routine was getting the "shutter closed" signal before the shutter was actually closed. Once this signal is received, the exposure sequence continues with its next instructions:

- logging the 1 kHZ DMI and height sensor data,
- switching the stage system out of drift control,
- moving to the next exposure site,
- closed looping wafer z,
- next shutter open/close cycle.

The process of logging the DMI data and the system state takes a couple seconds. This gave the shutter a couple seconds of extra time to shut before the stage moved. Longer exposure times were more likely to have the stage move while the shutter was open from the previous exposure. Prints were negatively affected in the following ways:

- Dose was impacted because the wafer would move and a single "exposure" would be split across two sites on the wafer.
- When the system goes out of drift control midway through the shutter cycle, part of the exposure would be done without drift control. Also, sometimes going in/out of drift control can cause a jump of several nm so the wafer would be exposed with two slightly shifted copies of the pattern.
- If the wafer stage moves to the next exposure site while the shutter is open, the original exposure is blurred while the stage is moving.
- The worst impact is the time the shutter is still open from the previous exposure once the wafer stage has moved to the next exposure site. This can be intuited as a "pre exposure". In this situation, a defocused image burns into resist at the new exposure site before closed loop of wafer z and before activation of drift control.

This bug was identified and patched in December 2019.

4. FEBRUARY 2020 PRINTING RESULTS

Figure 9 shows top-down SEM images of 13 nm half-pitch pillars (left), 12 nm half-pitch pillars (middle), and 11 nm half-pitch pillars (right) in resist printed in February 2020 with imaging conditions shown in Table 1 and material / processing conditions shown in Table 2. Figure 10 shows top-down SEM images of horizontal 9 nm half-pitch lines (left) and 8 nm half-pitch lines (right) in resist printed in February 2020 with imaging conditions shown in Table 1 and material / processing conditions shown in Table 2, with the exception that the resist thickness is 11 nm.

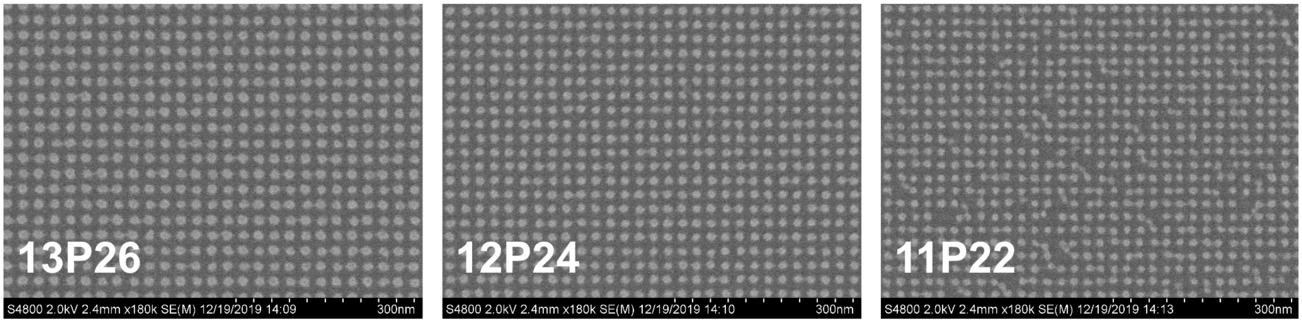


Figure 9: Top-down SEM images of 13 nm half-pitch pillars (left), 12 nm half-pitch pillars (middle), and 11 nm half-pitch pillars (right) in resist printed in February 2020 with imaging conditions shown in Table 1 and material / processing conditions shown in Table 2

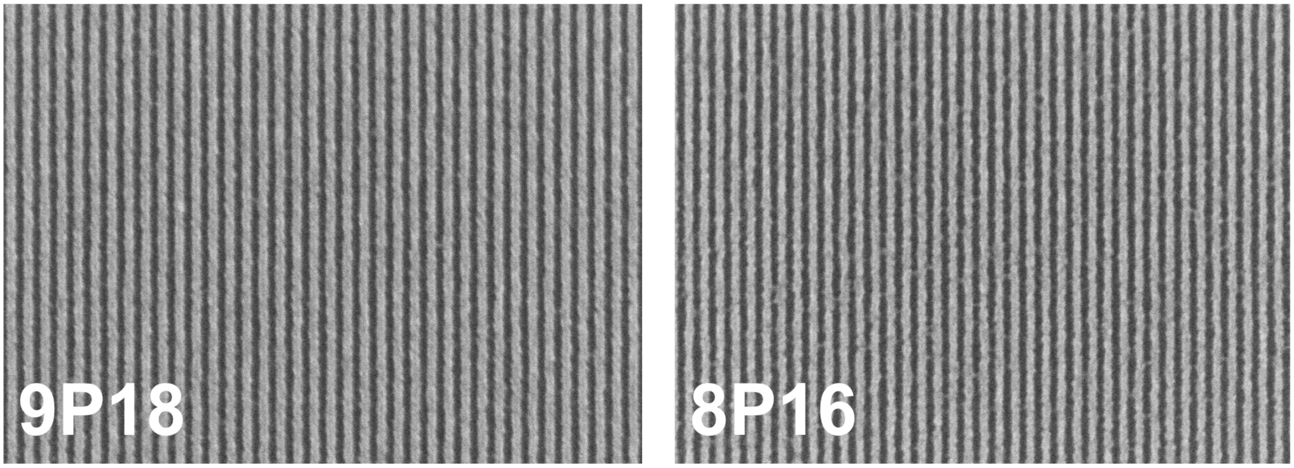


Figure 10: Top-down SEM images of horizontal 9 nm half-pitch lines (left) and 8 nm half-pitch lines (right) in resist printed in February 2020, using MET5 with imaging conditions shown in Table 1 and material / processing conditions shown in Table 2, with the exception that the resist thickness is 11 nm.

5. CONCLUSION

Vibration levels in MET5 exposures were reduced from 1.5 nm RMS to 0.8 nm RMS by tuning the vibration isolation system and removing non-compliant hardware. Alternating line widths were removed from frequency doubling exposures by replacing the Fourier-synthesis pupil scanner mirror. Focus-exposure-matrix outliers have been solved by patching a bug in the control software. 9 nm half-pitch lines and 8 nm half-pitch lines were printed in 11 nm thick MOx resist. 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.

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