EUV resist imaging below 50 nm using coherent spatial filtering techniques

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ABSTRACT

Lithography results using spatially-filtered coherent EUV radiation are presented. These experiments were done using a new 10× Schwarzschild optic and other significant upgrades for high stability and throughput of the system. Included are both single- and multiple-pitch images. A chemically-amplified EUV resist is shown performing at dense 50-nm linewidths and loose 25-nm features. High resolution polymers (HSQ and PMMA) were also tested and demonstrate dense 40-nm linewidths, which are the smallest 1:1 multi-pitch features attempted at this time.

Keywords: extreme ultraviolet lithography, EUV, Schwarzschild objective, spatial frequency doubling, aerial image contrast

1. INTRODUCTION

The ability to print small features at extreme ultraviolet (EUV) wavelengths is necessary for the timely development of resists and processing techniques for EUV lithography. There is much work that is still needed to push EUV resists to the levels necessary for commercialization.[1] By using a spatial frequency doubling coherent imaging method we can print high-contrast features at 50 nm and below. This allows for the examination of EUV photoresist limits while commercial tools are still being built.

The techniques used have shown the success of spatial frequency doubling lithography including low line edge roughness (LER)[2,3]. Many upgrades including a new 10× optic and e-beam written grating masks are now being used with the system. This has allowed for more robust experiments and higher (~6×) throughput.

2. SPATIAL FREQUENCY DOUBLING

By using spatially coherent 13.4-nm wavelength light and a 10×-demagnification optical system, high-resolution test patterns are exposed that extend well beyond the conventional resolution limits of the optic. The tool is capable of printing dense feature sizes below 50 nm with low line-edge roughness. Combining the 10× demagnification provided by the optic with the spatial-frequency doubling technique, 20× reduction of the object grating pitch is obtained. For example, 0.8-micron dense lines on the object grating will print 40-nm dense lines onto the resist-coated wafer. To get these small features, the line and space patterns are restricted to a single orientation and a dense 1:1 spacing.

The technique is most easily envisioned for a system configured to produce an image of a simple grating object. An aperture stop is designed to block the 0th diffracted order generated by the grating while allowing the +1 and –1 diffracted orders to propagate through the system and reach the image plane. In this configuration, a high-contrast spatial frequency doubled image of the grating pitch is produced (the F2X experiment).

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By restricting the field of view, the effective NA of the optic can be extended, up to almost the NA of the full annular pupil. Simulations have been done using CodeV to test the limits of this imaging process when utilizing the full NA of the optic. The theoretical doubling limit would be around 25-nm pitch features.

It is also possible to print several fine pitches in a single exposure using this system. The imaging configuration combines the spatial frequency doubling technique, discussed above, with a suitable multi-pitch grating. By suitably designing the object grating pattern and the spatial filter, multiple linewidths can be printed at once.[2] This method removes dose and processing variations from the printing experiments.

3. EXPERIMENTAL SETUP

3.1 - Experiment Apparatus

The coherent, monochromatic EUV radiation is provided by an undulator beamline (beamline 12.0.1 at the Advanced Light Source, Lawrence Berkeley National Laboratory). The beamline, containing a grating monochromator followed by a Kirkpatrick-Baez mirror pair (K-B), delivers radiation from the undulator to the imaging station. The undulator beamline provides continuously tunable illumination from 5-nm to 25-nm.

The F2X imaging station is housed in a vacuum chamber that consists of three main parts: the object housing, the optic chamber, and the load-lock.

Object Housing: The housing is a small structure that is situated before the optic chamber and is used primarily as a mount for the pinhole and object grating. It is translatable in X, Y, and Z, independently from the optic chamber. Near the focal plane of the K-B, an illumination pinhole is used as a spatial filter to provide uniform and coherent illumination of the object. The X-Y controls are used to position the housing such that the incoming light is incident directly on the pinhole. The object grating is mounted 10.795 mm above the pinhole and remains in the same fixed position relative to the pinhole. A 40×40 μm square transmission grating is used as an object and consists of a Si_3N_4 membrane patterned with Ni lines as an EUV absorber. The transmission masks were made at Lawrence Berkeley Lab's Nanowriter facility. The Z-axis provides focus control by altering the distance of the object from the optic.

Optic Chamber: The Optic Chamber is a cylindrical vacuum chamber that houses the 10× Schwarzschild optic. A specially designed aperture stop is mounted in the pupil plane of the system. Above the image plane is an EUV-sensitive CCD camera, used for alignment. An opening in the side of the optic chamber, in line with the image plane of the optic, provides access for the wafers by way of the load-lock.

Load-lock: The load-lock arm doubles as the wafer translation stage. It is located at the image plane of the optical system. The load-lock is a small, rectangular vacuum chamber equipped with an extendable arm and U-shaped wafer holder. A computer controlled motor translates the arm and wafer in and out of the optic chamber. The load-lock vastly increases the throughput for the F2X by reducing the amount of time it takes to load, expose, and remove a wafer. Only a small portion of the system now needs to be exposed to air, significantly reducing pump-down time. This also allows for alignment repeatability of the system between wafers.

3.2 - Wafer Handling/Resist Processing

Preparation: The F2X experiment is equipped to handle 4 inch wafers. Initial preparations are done at the UC Berkeley Microlab, where HMDS is applied using a prime oven for 60 seconds. The wafers are then individually packaged and brought to the synchrotron and placed in a small cleanroom. A wafer is then prepared by spinning on a resist and performing the Post Application Bake (PAB). The spin-on speed is determined empirically by measuring resist thickness and chosen such that there is approximately a 2.5:1 ratio of resist-thickness-to-line-width. PAB is performed according to manufacturers' instructions. The resist coated wafer is then repackaged in a container and covered in aluminum foil to block exposure to room lights. At the F2X station, the wafer is removed from its packaging and placed onto the load-lock arm. The load-lock is then pumped down and the wafer is inserted into the optic chamber for exposure.

Exposure: The optic itself contains 3 ball bearings that define the image plane. As the wafer is brought into the chamber it is placed on these bearings. The wafer is then decoupled from the load lock arm except when pushed to the next exposure spot. Dose control is accomplished by undulator tuning and altering the length of time the shutter is open to admit light. A computer program is given the dose parameters for the exposure run. The program automatically opens and closes the shutter for an exposure and translates the wafer forward. Current operations separate the exposed fields by 50 µm. Light intensity is monitored during the exposure run and adjusted as needed.

Development: After exposing, the wafer is removed from the load-lock, placed in a container and wrapped in aluminum foil. It is then brought back to the cleanroom where the Post Exposure Bake (PEB) and development are performed according to manufacturers' instructions. Delay time between removal from the load-lock and PEB start is approximately 30 seconds.

4. SINGLE-PITCH IMAGING

At this time we have printed 50-nm features in several resists. EUV 2D resist has been evaluated and reported previously.[2,3] We have also printed our best-ever full-field patterns at this linewidth. Figure 1 shows SEM images of dense 50-nm lines and spaces in Shipley XP9947W. These scanning electron microscope (SEM) images were obtained without gold coating of the samples. Some nonuniformities are visible over the full 16 square micron field, but it is clear that this resist is resolving these linewidths. Figure 2 is similar but has a higher dose and is therefore printing an overexposed pattern. The linewidth in this case is 40 nm (with 60-nm spaces). LER measurements were done at Intel

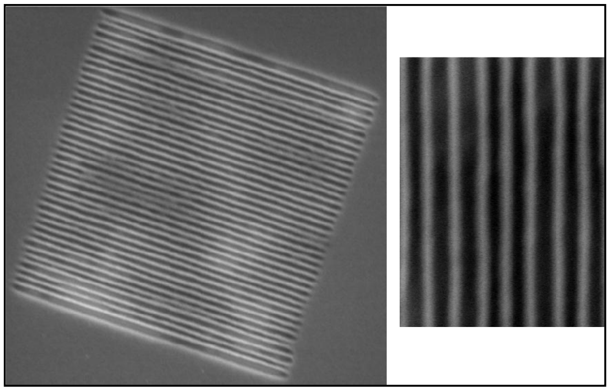


Figure 1 - Dense 50 nm l/s in Shipley XP9947W. 125 nm thick. No gold coating.

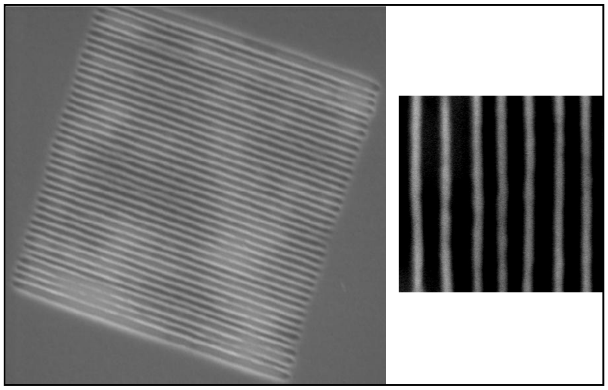
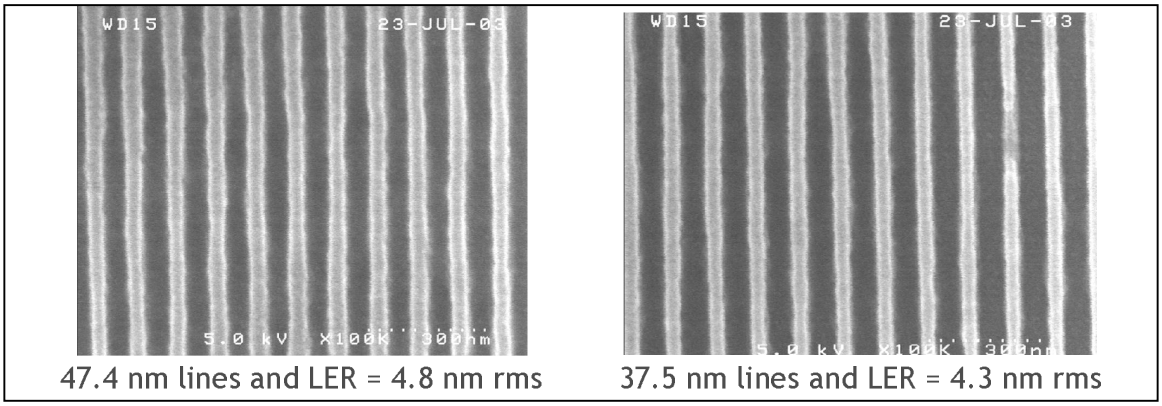


Figure 2 - Overexposed Shipley XP9947W: 40nm lines/60nm spaces. 125 nm thick. No gold coating.



47.4 nm lines and LER = 4.8 nm rms

37.5 nm lines and LER = 4.3 nm rms

Figure 3 - LER measurements for Shipley XP9947W (3 sigma values). Gold coated images.

with in-house tools. Gold coated images are shown in Figure 3. Three-sigma LER values are below 5 nm rms. As is typically seen, an overdosed line has a slightly better LER measurment.

5. MULTIPLE-PITCH IMAGING

As mentioned above, multiple-pitch printing extends the current F2X spatial-frequency doubling technique and incorporates four feature sizes in a single exposure. Currently, exposures are being done with a mask programmed for 70, 60, 50, and 40-nm dense lines/spaces on the wafer. Each pitch on the mask covers a quarter of a 40×40-μm square which produces a 2×2-μm field on the wafer (the full image is a 4×4-μm field).

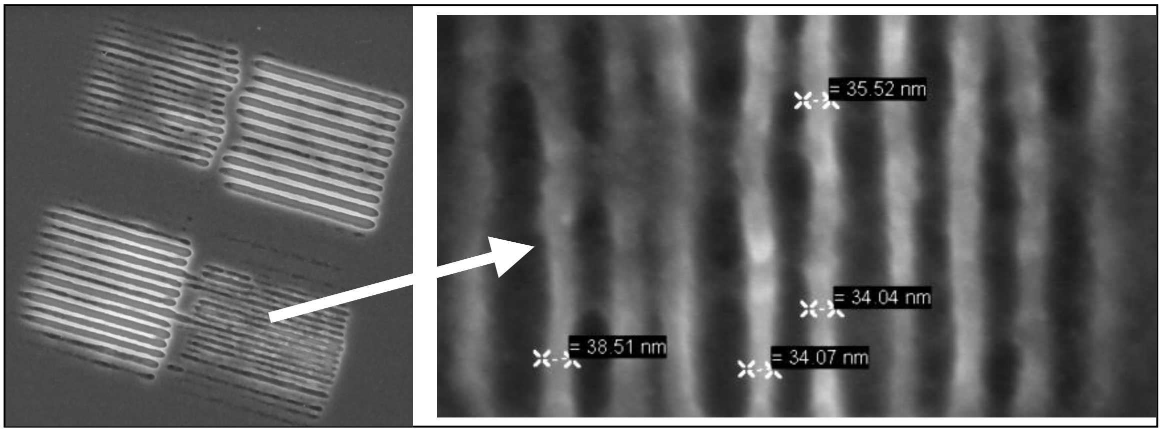


Figure 4 - Left: multiple pitch pattern (clockwise from upper left: dense 50, 70, 40, 60 nm lines). Right: semi-resolved sub-40 nm features. 125 nm thick. No gold coating.

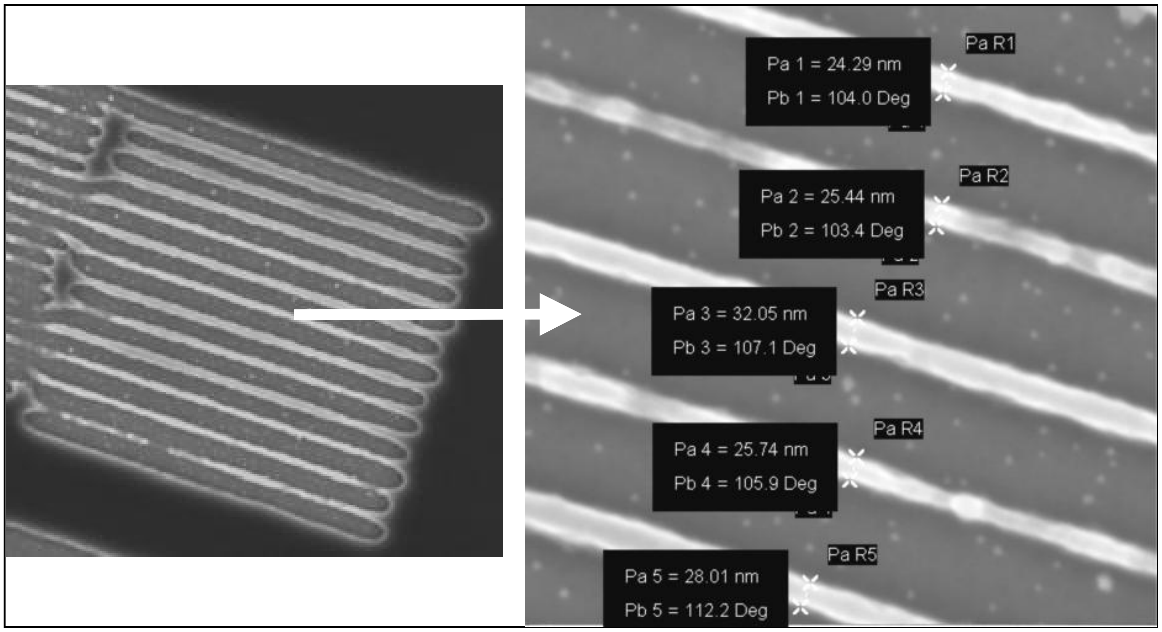


Figure 5 - Left: Overexposed 70 nm features in Shipley XP9947W. Right: Sub-30 nm features. 125 nm thick. Gold coated images.

One of the goals of this experiment was to investigate resolution limits and linearity of potential EUV photoresists. By producing several feature sizes during each exposure, wafer processing and development variations are removed from the experiments. There is still work to be done to maximize the uniformity in the printing but the tool is successfully imaging multiple pitches at once.

Tests have been done successfully using several chemically amplified EUV resists. Typically, dense 70, 60 and 50-nm features will print but the 40-nm ones are not well defined. Results also show the expected trend that the process window decreases as the features get smaller (70 nm vs. 40 nm). Best dose for each feature size also varied since there were no mask corrections implemented.

Figure 4 is an example of Shipley XP9947W. The 50-nm features in the upper left have already started disappearing but this is the best imaging of the 40-nm lines in the lower right. A larger image is shown at the right where 35-40 nm lines are visible although not printing sharply. Also of interest was the overexposing of these patterns. Figure 5 shows overexposed 70-nm features which show sub-30-nm loose-pitch lines.

Most recently, some multi-pitch exposures were done using non-chemically amplified resists. A sample image is shown in Figure 6. This picture has gold coating on the PMMA resist to help minimize SEM charging. The PMMA shows better the imaging capabilities of this multi-pitch mask. HSQ has also been exposed at EUV wavelength. Figure 7 shows (without gold coating) very clear linewidths for all feature sizes. Relative to EUV 2D the PMMA is approximately 4 times slower and the HSQ requires close to 11 times more dose.

6. CONCLUSIONS

As shown above, dense features of 50 nm have been resolved in chemically amplified resists. Sub-40 nm dense features were seen but did not show up cleanly. However, loose-pitch sub-30 nm features did show up clearly. LER was also shown to be below 5 nm (3 sigma rms) for dense 50-nm lines in Shipley XP9947W. When testing the imaging capabilities with PMMA and HSQ, all features from 70-40 nm were visible.

Resist resolution calculations were not done using the linewidth vs. dose method.[4] Theoretically, by printing multiple linewidths, EUV resist resolutions may be determined. This assumes a Lorentzian shape for the resist line spread function (LSF) for calculating the resolution

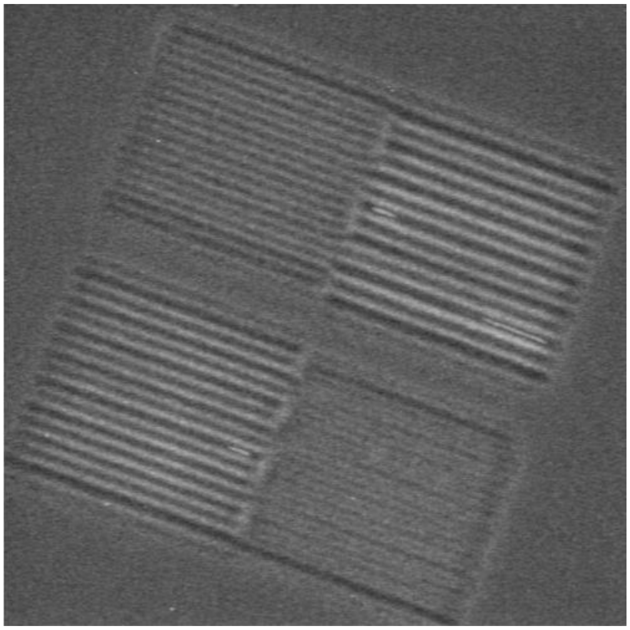


Figure 6 – Multiple-pitch image in PMMA resist (clockwise from upper left: dense 50, 70, 40, 60 nm lines). 100 nm thick. Gold coated image.

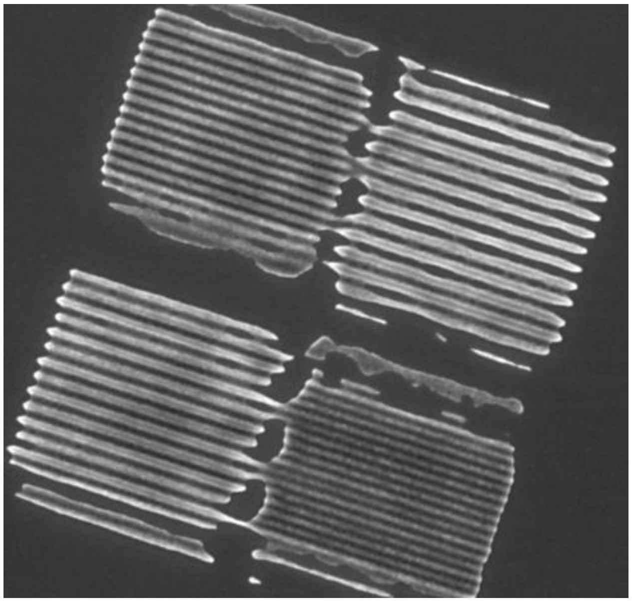


Figure 7 – Multiple-pitch image in HSQ resist (clockwise from upper left: dense 50, 70, 40, 60 nm lines). 62 nm thick. No gold coating.

(the full width at half maximum of the LSF). Unfortunately there is too much variation in our chemically amplified resist results to do this calculation. This variation originates from coherence effects, optic quality, and resist contrast.

Further work will be done pushing to smaller linewidths. Masks have been made that are designed to print single pitch fields of 40, 30, and 20 nm dense lines/spaces. Furthermore, aerial image contrast experiments can be done using other spatial filtering methods.[2] Combined, these configurations show great potential in evaluating the ultimate performance of resist materials for EUV lithography.

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REFERENCES

1. W. Yueh, H. Cao, M. Chandhok, S. Lee, M. Shumway, J. Bokor, “Patterning Capabilities of EUV Resists,” in Advances in Resist Technology and Processing XXI, Proc. SPIE **5376**, (2004).
2. M. D. Shumway, P. P. Naulleau, K. A. Goldberg, E. L. Snow, J. Bokor, “Resist evaluation at 50 nm in the EUV using interferometric spatial-frequency-doubled imaging,” in Emerging Lithographic Technologies VII, R. L. Engelstad, Ed., Proc. SPIE **5037**, 910-16 (2003).
3. M. D. Shumway, S. H. Lee, C. H. Cho, P. Naulleau, K. A. Goldberg, J. Bokor, “Extremely fine-pitch printing with a 10x Schwarzschild optic at extreme ultraviolet wavelengths,” in Emerging Lithographic Technologies V, E. A. Dobisz, Ed., Proc. SPIE **4343**, 357-62 (2001).
4. J. A. Hoffnagle, W. D. Hinsberg, M. I. Sanchez, F. A. Houle, “Method of measuring the spatial resolution of a photoresist,” Optics Letters, **27**, (20), 1776-8, (2002).

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