Measuring line roughness through aerial image contrast variation using coherent extreme ultraviolet spatial filtering techniques*

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(Received 1 June 2005; accepted 13 October 2005; published 2 December 2005)

Line edge roughness properties for an extreme ultraviolet photoresist (Rohm and Haas/Shipley 1 K) were investigated by varying the aerial image contrast of dense line and space patterns. Aerial image contrast variation was performed in single exposures by programming the modulation information on the mask. No background flood exposures were needed to reduce the contrast. The Micro Exposure Tool at Lawrence Berkeley National Laboratory was used for these experiments. Dense 50 nm lines and spaces were printed with contrast levels ranging from 86.4% to 46.8%. Coherence was programmed to be 0.1 for these experiments. Results show that an increase in the aerial image contrast causes a subsequent decrease in the line edge roughness (LER). Similar effects are seen for linewidth roughness (LWR). The LER varied from 3.3 nm (at 86.4% contrast) to 8.0 nm (at 46.8% contrast). LWR varied from 5.3 nm (at 86.4% contrast) to 12.8 nm (at 46.8% contrast). All values are three sigma root-mean-square. Only a couple of dense 30 nm features would print in this configuration. For these 30 nm lines and spaces, the best LER was 5.6 nm and LWR was 11.3 nm. © *2005 American Vacuum Society.* [DOI: 10.1116/1.2134717]

I. INTRODUCTION

Line-edge roughness (LER) properties of a photoresist can be investigated by varying the aerial image contrast of exposure patterns. In a typical experiment, the aerial image contrast is varied in a known way, and then the resulting effects on LER are measured. This is commonly done through a two-exposure process (pattern exposure and background flood exposure).[1] However, by using an aperture-plane filtering method, it is possible to print programmed contrast in a single exposure. Theory and computer simulations for this printing method were developed in a previous paper.[2] Single contrast exposures are achieved by varying the duty cycle of an object grating. If multiple contrasts are to be printed at once, then the transmission levels of the grating must also be altered. Since no flood exposure is needed in this technique, it can allow for more controlled contrast tests to help in the evaluation of resists.

This contrast variation method is essentially a two-beam interference technique. By tuning the relative strength of one of the beams against the other, it is possible to vary the contrast of the resulting image. Since line and space patterns in resists are the features of interest, it becomes advantageous to manipulate a simple object grating. Normal exposure of this modulated grating would also lead to the unwanted effect of producing different linewidths at different contrast levels. If, however, only the zero and one of the first orders are used to create the field mismatch at the wafer, the linewidth variation will not appear. The high-frequency duty cycle information becomes lost in the low-pass filter process.

II. CONTRAST EXPERIMENTS

These contrast experiments used one of the extreme ultraviolet (EUV) imaging systems—the Micro Exposure Tool (MET) at the Advanced Light Source (ALS) in Berkeley, CA. The tool has a large numerical aperture ($NA=0.3$) and is a 5× reduction system comprised of two annular aspheres. It is designed to print down to the 32 nm node, but has potential to go even smaller when printing in monopole and dipole modes. The field size is $0.2\times 0.6\ \mathrm{mm}^2$.

Wave front error was measured at-wavelength ($\lambda=13.5$ nm) and shown to be 0.8 nm root-mean-square (rms) in the first 37 Zernikes.[3] One great advantage to this tool, which is attached to the highly coherent ALS, is that it has a set of rotating illumination mirrors which can send any desired pupil fill into the system. Therefore, coherence can range from 0.1 to 1 and all manner of illumination schemes (annular, monopole, dipole, quadrupole) are possible.

The mask incorporated duty-cycle modulation, as discussed earlier, and used the METs NA limits to filter out unwanted orders. The reflection mask for the MET was designed to print both 50 and 30 nm dense line and space patterns. It was written with the Nanowriter at Lawrence Ber-

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*No proof corrections received from author prior to publication.

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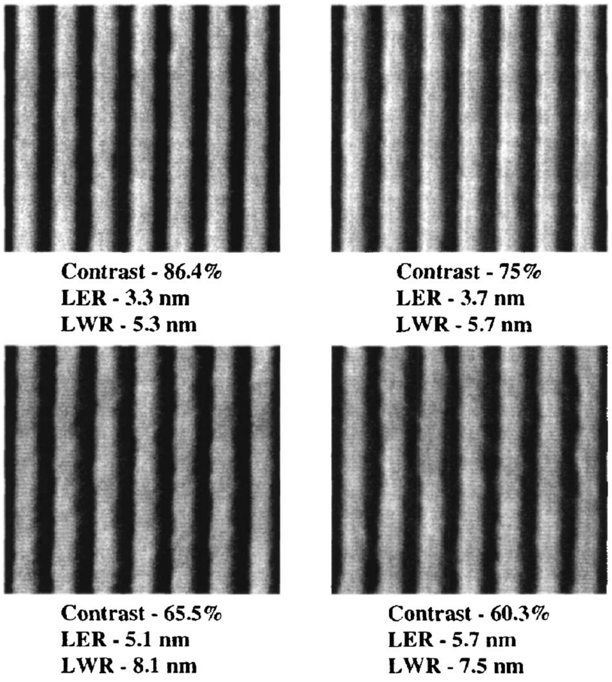


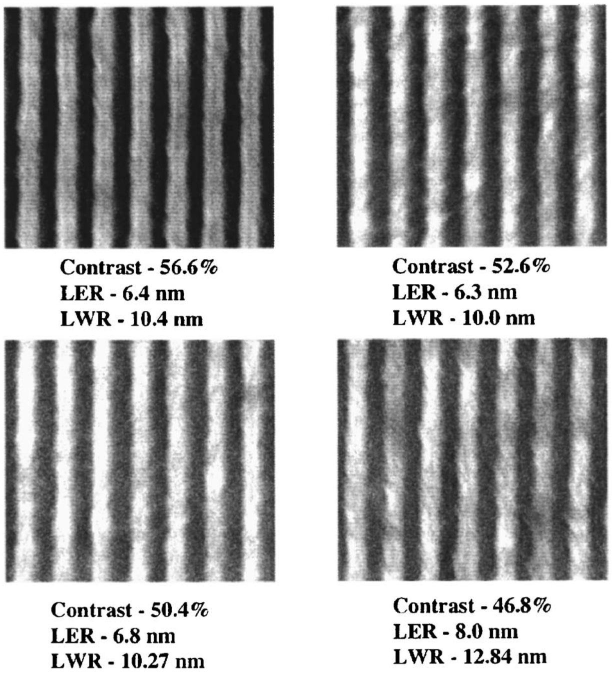
Contrast - 86.4%
LER - 3.3 nm
LWR - 5.3 nm

Contrast - 75%
LER - 3.7 nm
LWR - 5.7 nm

Contrast - 65.5%
LER - 5.1 nm
LWR - 8.1 nm

Contrast - 60.3%
LER - 5.7 nm
LWR - 7.5 nm

FIG. 1. Dense 50 nm lines and spaces in Shipley 1 K for the four highest contrast levels that printed. Resist thickness—125 nm.



Contrast - 56.6%
LER - 6.4 nm
LWR - 10.4 nm

Contrast - 52.6%
LER - 6.3 nm
LWR - 10.0 nm

Contrast - 50.4%
LER - 6.8 nm
LWR - 10.27 nm

Contrast - 46.8%
LER - 8.0 nm
LWR - 12.84 nm

FIG. 2. Dense 50 nm lines and spaces in Shipley 1 K for the lowest four contrast levels that printed. Resist thickness—125 nm.

keley National Laboratory. After mask fabrication, including etch bias effects, available contrast levels ranged in ten steps from 86.4% to 37.8% for each of the two pitches. Coherence was set at 0.1 and the resist used was Rohm and Haas/Shipley 1 K at a thickness of 125 nm. The LER for the 250 nm lines and spaces on the mask (50 nm at the wafer) was 9.3 nm in mask space or 1.86 nm at the wafer. As the results will show, this mask roughness is smaller than the measured LER when printing in the resist.

III. LER RESULTS

Figure 1 shows the highest contrast (86.4%) results for the 50 nm lines and spaces. All roughness values are three sigma rms. The software program used to do the roughness analysis was SUMMIT.[4] This program was setup to do low-pass two-dimensional prefiltering and use a threshold algorithm of 50% for line edge detection. The lowest two contrast levels (43.3% and 37.8%) did not print linewidths close enough to 50 nm (the necessary dose-to-size level). Contrast exposures from the 37.8% field only printed linewidths down to 80 nm. Similarly, the 43.3% contrast field printed lines to 70 nm. Both LER and linewidth roughness (LWR) measurements were taken for the remaining eight contrast points. All linewidths used fell between 45 and 55 nm. Linewidth roughness is similar to LER except that it looks at variation with respect to the width of the line rather than the sides. It is believed to be a better metric when determining transistor performance and current leakage.[5]

Figure 2 shows the eight contrast steps with their corresponding SUMMIT data values. Analysis of this 50 nm data shows a definite trend—a decrease in contrast will contribute to an increase in line edge roughness and a measurable increase in linewidth roughness. These LER and LWR data are plotted in Fig. 3. Both LER and LWR follow similar upward trends toward more roughness as contrast is decreased. A linear fit of this data shows that Shipley 1 K's LWR is, on average, 1.6 times larger than its LER. If line edge roughness of the left and right sides were to vary randomly and independently of each other, then $\mathrm{LWR} = \sqrt{2} \times \mathrm{LER}$.[5] The results for these MET contrast exposures come close to this relationship.

Some 30 nm dense lines and spaces were also printed in Shipley 1 K as shown in Fig. 4. Unfortunately, very few of the dense 30 nm features printed sufficiently well for a full contrast analysis to be done. However, the images in Fig. 4 are some of the best performing dense features printed in an EUV chemically amplified resist. These images are from the two highest contrast levels (86.4% and 75.0%) and show

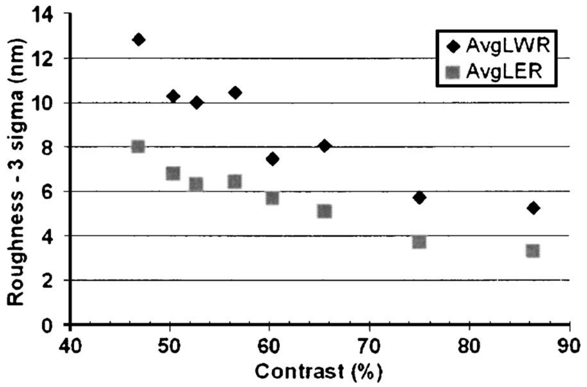


FIG. 3. Roughness seen in Shipley 1 K resist for dense 50 nm lines as a function of contrast. Resist thickness—125 nm.

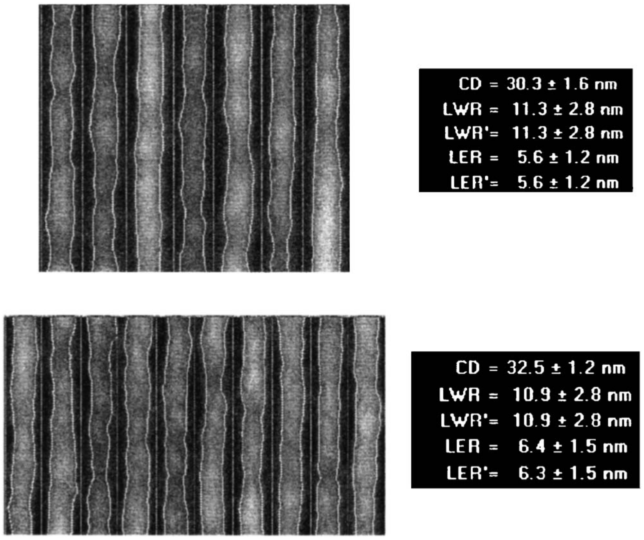


FIG. 4. Dense 30 nm features printed in Shipley 1 K using the MET. Resist thickness—125 nm.

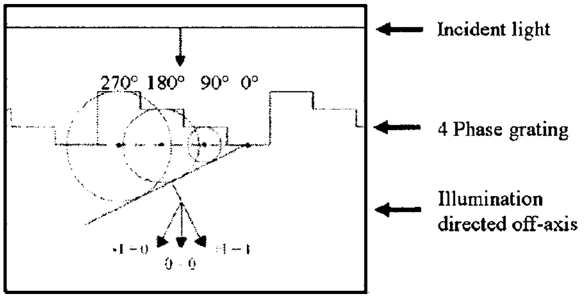


FIG. 5. Diffracted orders from a linear phase grating. For the lowest orders, light is only directed into the +1 direction (modified image from Ref. 9).

dense lines and spaces of 30.3 and 32.5 nm. The 30.3 nm lines had LWR of 11.3 nm and LER of 5.6 nm. The 32.5 nm lines had LWR of 10.9 nm and LER of 6.3 nm.

Other research groups have shown similar trends in regards to LER (higher contrast images produces lower LER). IBM has done work at 250 nm lines and spaces.[1] Williamson did work at UC Berkeley also with 250 nm features.[6] A detailed look at features around 100 nm was done at AMD.[7] This last work showed better agreement between LER and image-log-slope (ILS) than between LER and contrast over many different resists. It was shown that variations in feature type and illumination would make contrast a weaker predictor of LER than using ILS. Since the MET contrast exposures were done at 50 nm and for only one resist, switching to ILS is not necessary but can be done.[8]

IV. DIRECTIONAL CONTRAST

An interesting extension to this aerial image contrast research is to look at incorporating phase technology. Previously, the duty cycle and absorption strength were the only allowed variables. However, if phase is added as a mask fabrication possibility, contrast designs can be created. In fact, if a multiple-phase mask and a coherent source were available then this contrast technique could work in a conventional stepper where spatial filtering in the aperture plane is not always feasible. The main concept is to fuse the single-exposure contrast technique with a modified linear phase grating.[9] Figure 5 shows an example of a linear phase grating. The incident light entering the grating from the top is redirected into the +1 order. No light is directed in the 0 or −1 orders.

By using phase manipulation to remove these low orders, no aperture filtering is needed. As such, without filtering at all, only select pitches would be available for any individual imaging system. With the first order being directed off toward the edge of the pupil, manipulation of the phase mask can vary the contrast. By simply varying the transmission amounts through the four different phase levels (0°, 90°, 180°, and 270°), the diffracted fields will no longer completely cancel out the zeroth order. To get strong contrast manipulation it is useful to change the transmission amounts of two adjacent phase levels. For example, reducing the amount of incident light transmitted through the 0° and 90° levels by 50% and letting 100% of the 180° and 270° light through the system will reduce the image contrast by 48%. A whole range of such transmission levels is shown in Fig. 6.

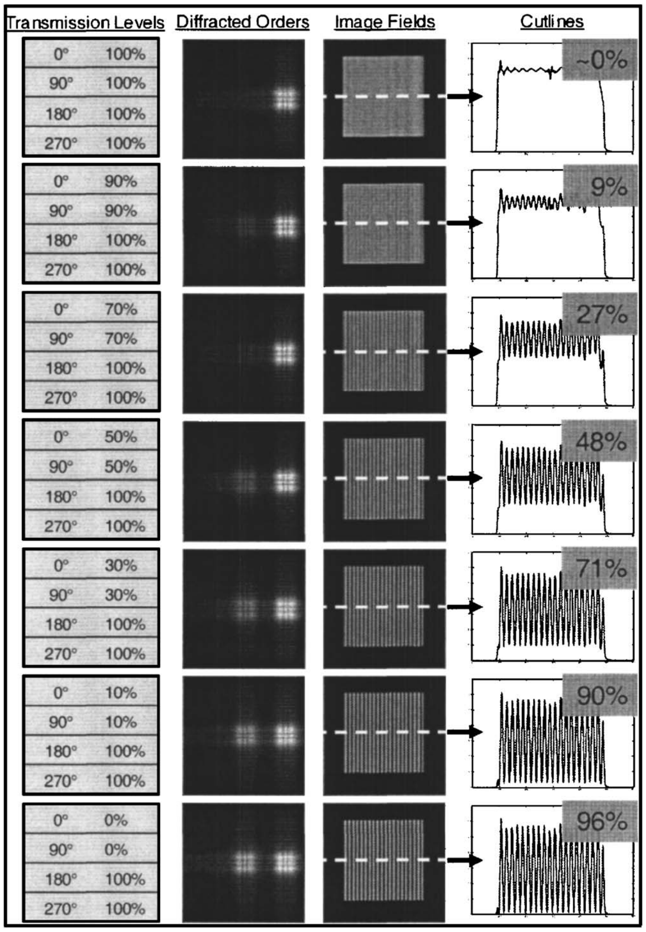


FIG. 6. Simulations on contrast variation using an absorptive phase mask. As less light is allowed through the 0° and 90° phase levels, the image gains contrast.

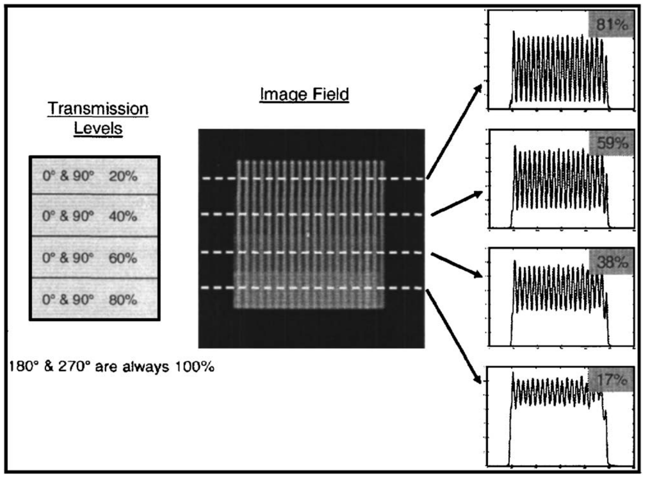


FIG. 7. Multiple-contrast imaging using an absorptive phase mask. Four different transmission amounts are used for 0° and 90° phase levels. These transmission amounts produce different contrasts in the image field. Cutlines for each transmission amount are on the right.

These simulations show from left to right: (1) transmission amounts for each phase level in the grating, (2) the diffracted orders in the pupil plane, (3) line and space fields after reimaging the absorptive phase grating, and (4) center cutlines through each of the image fields in (3).

In the first case, all phase levels are completely transmitting and the contrast is essentially zero. This is because the +1 order is not being interfered with by any other orders. Once a second order gains some strength (as in any of the other cases) then there will be at least some modulation of the image field. These simulations were done using spherical illumination of the phase mask, but plane wave illumination would work as well.

In a typical phase mask there already is some attenuation difference in the phase levels and this would need to be taken into consideration. For directional contrast experiments, more emphasis is placed on absorption levels. In the aerial image contrast technique used earlier in this article, duty cycle was the more important variable. Figure 7 shows an example of a directional contrast mask with four different absorber levels. As demonstrated, multiple contrasts will be printed as dose is varied.

V. CONCLUSIONS

For this EUV investigation, contrast variation was integrated into the mask design. Through duty cycle changes in the object grating, the relative strengths of the diffracted orders were manipulated. By using spatial filtering, only the 0 and +1 orders were used to create the field mismatches. The imbalances in the orders resulted in different image contrasts at the wafer plane. As constructed, the duty cycles on the mask did not print on the wafer since all higher orders were filtered out. This research demonstrated contrast variation by printing the different contrast levels using multiple doses. As mentioned earlier, in order to balance the dose levels in this configuration, attenuation would be a useful variable in the mask design.[2]

Results show that an increase in the aerial image contrast causes a subsequent decrease in the LER. Similar effects are seen for LWR. Averaged over the data, LWR was 1.6 times larger than LER. The lowest LER seen for dense 50 nm lines and spaces in Shipley 1 K was 3.3 nm rms (three sigma). This was in the highest contrast case (86.4%). As contrast decreased to 46.8%, LER grew to 8.0 nm rms (three sigma). The highest contrast case, using these MET exposures, produced the same LER in Shipley 1 K (3.3 nm rms) as was seen in another high-contrast EUV tool (F2X system).[8]

Other studies have shown similar trends with regards to line roughness for many different resists. Large line roughness is certainly not solely caused by low image contrast, but tools like this contrast variation technique can be used to effectively monitor resist performance. The work in this article has shown photon-based contrast experiments using the smallest linewidths to date.

ACKNOWLEDGMENTS

The authors thank Robert Brainard (Rohm and Haas/Shipley), Eric Snow and Greg McIntyre (UCB), Heidi Cao and Sang Hun Lee (Intel), Paul Denham, Seno Rekawa, and Drew Kemp (LBL). This research has been supported by the Semiconductor Research Corporation (Contract No. 96-LC-460), the DARPA Advanced Lithography Program (Grant No. MDA972-97-1-0010), and Sematech. The work was performed in part at Lawrence Berkeley National Laboratory. Lawrence Berkeley National Laboratory is operated under the auspices of the Director, Office of Science, Office of Basic Energy Science, of the US Department of Energy.

[1] M. I. Sanchez, W. D. Hinsberg, F. A. Houle, J. A. Hoffnagle, H. Iyo, and C. Nguyen, Proc. SPIE **3678**, 160 (1999).
[2] M. Shumway, P. Naulleau, K. Goldberg, E. Snow, and J. Bokor, Proc. SPIE Int. Soc. Opt. Eng. **5037**, 910 (2003).
[3] K. Goldberg, P. Naulleau, P. Denham, S. Rekawa, K. Jackson, J. Liddle, and E. Anderson, Proc. SPIE **5374**, 64 (2004).
[4] SUMMIT software developed by Patrick Naulleau; http://euvl.com/summit/.
[5] H. Cao, J. Roberts, J. Dalin, M. Chandhok, R. Meagley, E. Panning, M. Shell, and B. Rice, Proc. SPIE **5039**, 484 (2003).
[6] M. Williamson and A. Neureuther, Proc. SPIE **5039**, 423 (2003).
[7] A. Pawloski, A. Acheta, I. Lalovic, B. La Fontaine, and H. Levinson, Proc. SPIE **5376**, 414 (2004).
[8] M. Shumway, Ph.D. thesis, University of California, Berkeley, 2004.
[9] G. McIntyre and A. Neureuther, Proc. SPIE **5040**, 162 (2003).