# Line edge roughness characterization of sub-50nm structures using CD-SAXS: Round-robin benchmark results*

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## ABSTRACT

The need to characterize line edge and line width roughness in patterns with sub-50 nm critical dimension challenges existing platforms based on electron microscopy and optical scatterometry. The development of x-ray based metrology platforms provides a potential route to characterize a variety of parameters related to line edge roughness by analyzing the diffracted intensity from a periodic array of test patterns. In this study, data from a series of photoresist line/space patterns featuring programmed line width roughness measured by critical dimension small angle x-ray scattering (CD-SAXS) is presented. For samples with periodic roughness, CD-SAXS provides the wavelength and amplitude of the periodic roughness through satellite diffraction peaks. In addition, the rate of decay of intensity, termed an effective "Debye-Waller" factor, as a function of scattering vector provides a measure of the fluctuation in line volume. CD-SAXS data are compared to analogous values obtained from critical dimension scanning electron microscopy (CD-SEM). Correlations between the techniques exist, however significant differences are observed for the current samples. Calibrated atomic force microscopy (C-AFM) data reveal large fluctuations in both line height and line width, providing a potential explanation for the observed disparity between CD-SEM and CD-SAXS.

**Keywords:** Critical Dimension Metrology, Line Edge Roughness, Extreme Ultraviolet Lithography, Scatterometry

## 1. INTRODUCTION

The targeted amplitudes of line edge roughness (LER) and line width roughness (LWR) for extreme ultraviolet (EUV) lithography are currently sub-nanometer. The small scales of these features combined with the electron beam sensitivity of many photoresists challenges dimensional metrology based on electron and optical beam methods. CD-SAXS is being explored for its capability to quantify CD, pitch, line edge roughness and cross sectional profile in periodic line and space (i.e., grating) structures. The technique is based on transmission small angle x-ray scattering and uses a high energy x-ray beam to pass non-destructively through silicon substrates. As the beam passes through a periodic pattern, the diffracted intensity is recorded on a detector (see fig. 1). The pattern shape and size are then extracted from a fit of the diffracted intensity. Prior work with model grating patterns in polysilicon with programmed, periodic roughness has demonstrated the capability of CD-SAXS for LER metrology in patterns with critical dimension ≈ 100 nm.[1-4] Here, we present CD-SAXS data for line/space patterns with programmed line width roughness produced using EUV lithography. The patterns have a critical dimension of ≈ 40 nm line width and a nominal line/space ratio of



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1:3. The CD-SAXS data are compared to analogous measurements of critical dimension, periodicity, sidewall angle, and amplitude of LWR obtained from CD-SEM.

The potential for LER and LWR characterization using CD-SAXS originates in the capability of scattering methods to directly measure distributions of dimensions over a large number of samples. Specifically, the distributions of pitch and line width both contribute to the rate of decay of diffracted intensity as a function of scattering vector. This method of analysis is general to all diffraction and is characterized by the Debye-Waller factor in atomic crystallography to describe thermal vibrations. Using the analogy of thermal vibrations on a lattice as an analogy to line edge position variations, we can employ an "effective" Debye-Waller factor to describe line edge and line width roughness.[4] However, other factors such as the pattern cross sectional shape can affect the precision of values of LER extracted from this method. To evaluate the capability of CD-SAXS to quantitatively measure LER and LWR in sub-50 nm structures using this effective Debye-Waller factor, we have designed a series of samples that provide a secondary method of LER and LWR characterization. These line/space patterns feature a programmed, periodic line width roughness created by the placement of "tabs" of predetermined amplitude, size, and placement along the line edge. The resulting periodic roughness can be directly measured by a secondary, or "satellite", diffraction axis where the intensities are directly related to LER and LWR amplitude.[5] Results of these measurements can be used to assess the potential of the "Debye-Waller" method to measure LER in line/space patterned areas using CD-SAXS.

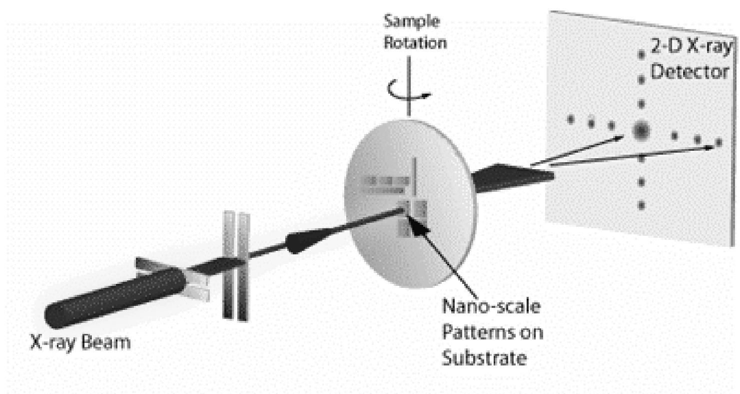


Fig. 1. Schematic of the CD-SAXS geometry, showing the measurements performed in transmission through a silicon substrate. The schematic illustrates the test patterns on the source side of the substrate, however measurements with the patterns on the detector side of the substrate produce equivalent results. The experiments described here were performed with the patterns on the detector side of the substrate to reduce potential effects from beam damage. The beam is shown relative to the sample and the detector, illustrating the scattering angle, $2\theta$.

## 2. EXPERIMENTAL

A reticle with line/space patterns of programmed LWR has been designed and fabricated for exposure using EUV lithography. The designed features include line/space arrays in patterned areas over an area exceeding 100 μm × 100 μm. The line widths are nominally constant within a given patterned area, and line widths across the entire reticle range from 25 nm to 60 nm. The nominal line/space ratio is 1:4. Line width and line edge roughness samples with programmed roughness were created by adding "tabs", similar to optical assist features common in photoresist image design, with a pre-determined distance between centers along the line edge, given the label "roughness wavelength" in this report. The distance of the tab edge from the nominal line edge is hereby referred to as the tab amplitude and ranges from 9 nm to 30 nm with a nominal roughness wavelength of 100 nm. Photoresist with 60 nm thickness was used to pattern 200 μm × 600 μm line/space grating using EUV photolithography ($\lambda$ = 13.6 nm). For this study, we have selected a LWR structure with designed line width of 35 nm with 175 nm pitch and 15 nm programmed roughness amplitude to be printed on a 300 mm diameter wafer. The wafer was exposed by EUV with a 9 x 18 FEM (Focus Exposure Matrix) and subset of 36 FEM sites were used for CD-SAXS benchmark test with CD-SEM.

Thirty-six line measurements were performed per grating using CD-SEM in the Advanced Technology Development Facility (ATDF) at ISMI/SEMATECH. In figure 2, a representative CD-SEM image shows the periodic line width roughness in top-down view. This was achieved with an automated recipe which stepped a 3x3 matrix of regular (20 μm) intervals over the grating in both x and y directions, performing non-unique pattern-recognition at each of the 9 positions, and at each position placing a 2μm long measurement image over four random lines. CD and LWR values were calculated by the tool for all four lines in the image. Each image consisted of 512 line scans, so that LWR could be calculated by the ISMI best-known method, which has been defined elsewhere.[6]

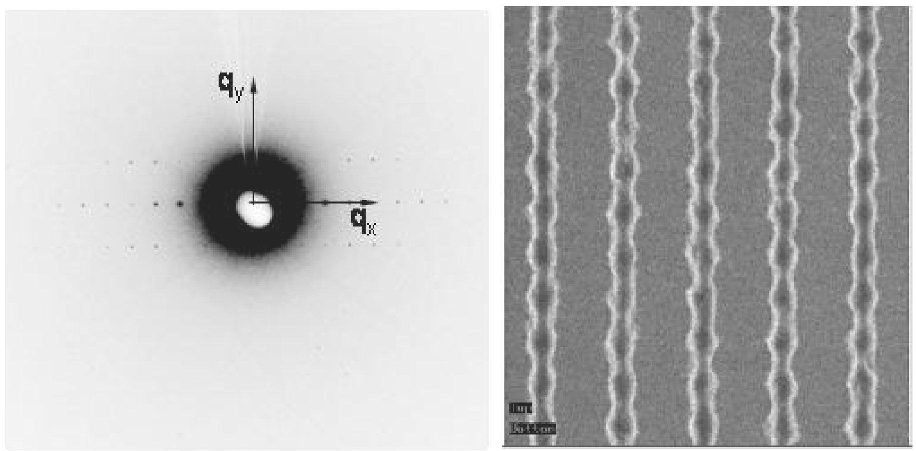


Fig. 2. CD-SAXS 2-dimensional detector image of a sample with programmed periodic line width roughness (left). The scattering vectors along the diffraction axis ($q_x$) and normal to the diffraction axis ($q_y$) are shown. In addition to the main diffraction axis at $q_y = 0$ nm$^{-1}$, a series of satellite diffraction peaks are found at $q_y = +/- 2\pi/L$, where L is the wavelength of the tab spacing. A top down CD-SEM image displays the magnitude and periodicity of the programmed roughness in the photoresist line/space pattern (right).

CD-SAXS measurements were performed at the 5-ID-D beamline, operated by DND-CAT, at the Advanced Photon Source, part of Argonne National Laboratory, as described elsewhere.[4] As illustrated schematically in figure 1, CD-SAXS records the diffracted intensity from an array of patterns in transmission through a silicon substrate. An X-ray energy of E = 17 keV was selected using a monochromator, corresponding to a wavelength of $\lambda = (0.0729 \pm 0.0001)$ nm. A focusing mirror and beam defining slits produced an approximately square beam of 100 μm x 100 μm at the sample surface. The sample was oriented with the silicon substrate facing the incoming beam to reduce the possibility of beam damage, where the transmission through a 300 mm diameter silicon wafer is ≈ 45%. Diffracted intensity was recorded on a 2-Dimenionsal CCD detector with square pixels of side length (78.75 ± 0.05) μm. The sample-detector distance was set to be (739.0 ± 0.1) cm. The direct beam was blocked by a circular beamstop to prevent detector damage. Intensities were recorded as a function of the scattering vector, q (= $4\pi/\lambda \sin(\theta)$, where 2θ is the angle of diffraction), and x denotes an axis parallel to the main axis of diffraction. The beam origin (i.e. q = 0) is defined at the beam center on the detector. X-rays diffracted from the test pattern are symmetrically diffracted about the beam center, making I(q) = I(-q). As a result, the intensities presented here are an average of I(q) and I(-q), and are hereafter labeled simply as q. The Fourier space plane, $q_x - q_y$, is closely approximated by the detector plane with the $q_x$ axis oriented along the main axis of diffraction. The data reported here are taken with the beam at normal incidence to the substrate plane.

Due to a lack of phase information in the scattered intensity measured by CD-SAXS, the data must be modeled assuming an average cross sectional shape of the line/space pattern. Previous work has demonstrated the applicability of a trapezoidal cross section to many relevant patterns produced by photolithography. For samples where the cross sectional shape deviates from a symmetric trapezoid, the result of the CD-SAXS modeling provide the effective trapezoidal shape with the same line volume and average dimensions. The uncertainty stated in this report is therefore the uncertainty in the dimensions of the effective trapezoid.

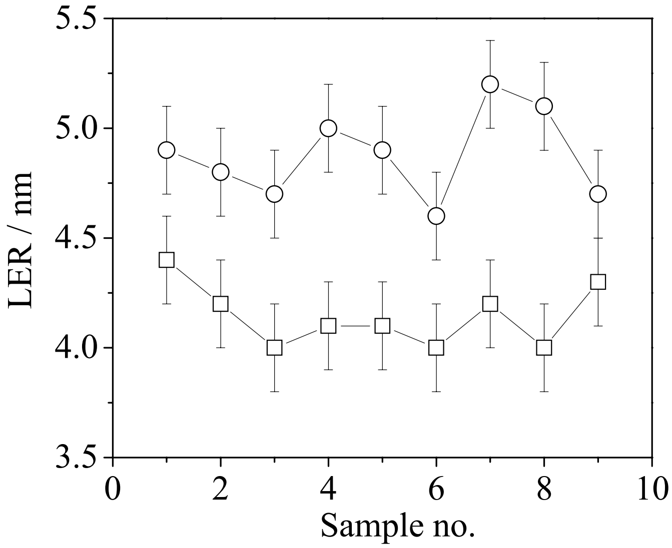


Fig. 3. CD-SAXS results for line edge roughness (LER) for a series of line/space photoresist patterns. LER is calculated by two methods, namely the ratio of the main diffraction peak intensity to the satellite peak intensity (solid symbols) and by the effective Debye-Waller factor (open symbols). The Debye-Waller method consistently produces values of 0.5 nm to 1.0 nm lower. Error bars represent the standard uncertainty of the measurement. The lines are drawn to guide the reader's eyes.

## 3. RESULTS AND DISCUSSION

Figure 2 displays a typical diffraction pattern obtained from line/space patterns with periodic LWR. In addition to the main diffraction axis observed along $q_y = 0$, two parallel, or "satellite", axes of diffraction are observed symmetrically above and below the main axis. The parallel diffraction axes are characteristic of a programmed line edge roughness with a single period L that travels along the line direction. The satellite diffraction peaks then occur at $q_y = \pm 2\pi/L$. The satellite peak diffraction is entirely produced by the constructive interference of the periodically placed tabs on the line edges, and the intensity is therefore directly relatable to the volume of LWR. A convenient method for extracting a quantitative measure of the amplitude of periodic LWR uses the ratio of intensities of diffraction peaks along the satellite diffraction axis and the main diffraction axis.[5] The result of this method of analysis does not incorporate uncorrelated, or non-periodic, roughness. In contrast, the rate of decay of intensity along the main diffraction axis, represented by an effective Debye-Waller factor, is a measure of the total fluctuation in line shape and pitch.

Figure 3 shows the results of LWR measurements made using both the ratio and Debye-Waller methods from CD-SAXS. The LWR obtained from the ratio method is always ≈ 1 nm smaller than the analogous value obtained by the Debye-Waller method. The higher values of LWR from the Debye-Waller method likely reflect the additional non-periodic component of the roughness. While the samples were designed with largely periodic roughness, the CD-SEM images indicate the existence of a 1 nm uncorrelated roughness is within reason. For ideal programmed LER grating model, the LWR is twice of LER. But due to low data quality from the satellite peaks of other patterns, we take $6\sigma_t$ to compare LWR ($3\sigma$) by CD-SEM hereafter.

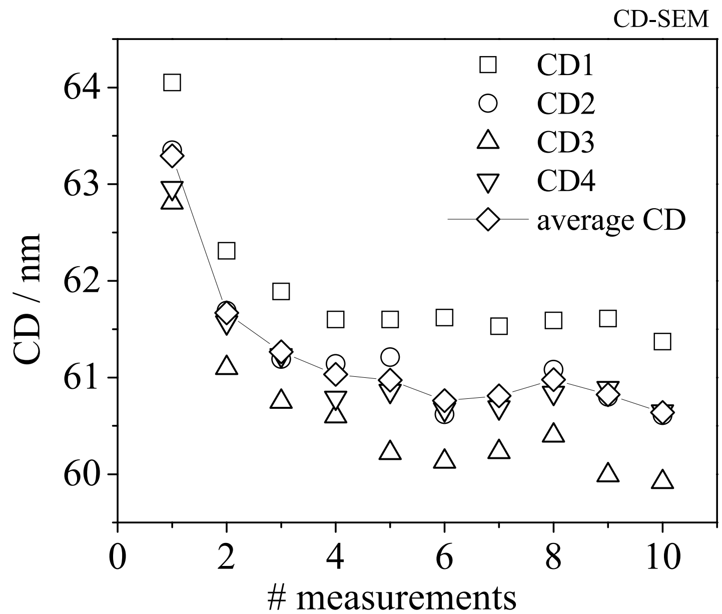


Fig. 4. Feature stability during continuous measurements by critical dimension scanning electron microscopy (CD-SEM). Shown is the critical dimension (CD) measured at four sites (CD1, CD2, CD3, and CD4) as a function of the number of measurements. Each measurement was performed for a constant amount of time. CD-SEM measurements were performed with a beam accelerating voltage of 800 V to achieve high image resolution, high contrast of feature edges, and low noise for roughness measurements.

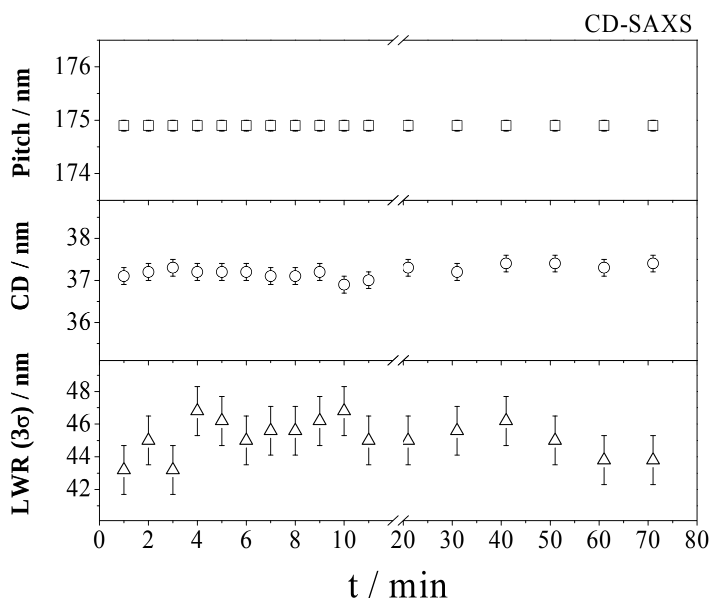


Fig. 5. Feature stability during continuous measurements by CD-SAXS. Plotted are the line/space pitch (top), critical dimension (CD) (middle), and the line width roughness (LWR) (bottom) as a function of exposure time, t, in the x-ray beam. Data from the first 10 min were collected continuously for 1 min each, and subsequent data points represent data collection times of 10 min. Each data set is measured from exposure of the same spot of one sample, the break in the x-axis is provided for presentation clarity only. The error bars represent the standard uncertainty of the measurement.

A primary issue of electron beam based measurements is the sensitivity of organic photoresists to beam damage, making dimensional measurements both destructive to the pattern and measurement time dependent. In figure 4, CD-SEM measurements of the photoresist patterns used in this study were performed more than 10 times on the same sample area. The critical dimension is observed to follow a well documented phenomena beam induced CD shrinkage, reducing CD by ≈ 2 nm during multiple exposures. While x-rays can also be damaging to organic materials, the use of high energies (> 10 keV) results in beam energies that are far above typical adsorption energies of organic materials. Any low energy component of the incident beam will have a small transmission through silicon, making the silicon substrate an effective filter of damaging radiation before the test pattern is exposed. The data in figure 5 demonstrate that to within the sub-nm uncertainty of the measurement, pitch and CD are constant over long exposure times. Higher fluctuations are observed in LWR, however the values are constant within the larger uncertainties in these measurements. We note that a typical exposure time for the measurements presented here are less than 60 sec. As a result, the data indicate that CD-SAXS is a non-destructive measurement for this EUV photoresist formulation and does not suffer from beam induced CD shrinkage.

In figure 6, results of CD measurements from CD-SAXS and CD-SEM are compared for a series of patterns exposed under varying degrees of focus. For both series of constant dose, the CD obtained from CD-SAXS, which represent the volume averaged line width over the entire line height, consistently fall between the top and bottom width measurements from CD-SEM. However, the CD closely approximates the top width values from CD-SEM in the higher dose sample, while the values are closer to the average of the top and bottom widths in the lower dose. The disparity in the quantitative relationship between CD-SAXS and CD-SEM across these two samples is potentially due to a disparity in the two samples from the trapezoidal approximation. As previously stated, dimensions obtained from CD-SAXS data in this work represent the dimensions of an effective trapezoidal cross section for the line/space pattern. As a result, CD-SAXS is providing the first moment of the entire line volume. In contrast, the top-down imaging of CD-SEM provides a top width and bottom width of the line. In the limit of a perfect symmetric trapezoidal cross section, the average of the top and bottom width is equivalent to the volume average. However, non-trapezoidal cross sections can affect the relationship between the true mass average line width and the average between the top and bottom dimensions. As an example, a parabolic sidewall will feature an average line width that approximates the bottom width since most of the mass is at the bottom of the line. The difference observed here is consistent with a cross sectional shape that varies with dose.

In figure 7, the LWR obtained from CD-SEM is compared with the results of both the ratio and Debye-Waller methods of CD-SAXS. We note that the LWR values obtained from both CD-SEM and CD-SAXS represent 3 standard deviations (labeled $3\sigma$) from the average line width. The values of LWR from the Debye-Waller method are consistently larger than those of the ratio method. The reasons for this disparity are likely the same as those for the disparity in average CD described above, namely the inclusion of random roughness in the Debye-Waller method. The roughness obtained from CD-SEM should also include both random and periodic contributions, however the values are found to be consistently lower than both values from CD-SAXS. The origin of these differences is still being explored, however we note that as a transmission measurement, CD-SAXS is sensitive to overall line shape fluctuations and does not specifically measure only line width fluctuations. As a result, CD-SAXS data incorporate, among other fluctuations, line width roughness, line height roughness, and fluctuations in sidewall angle.

In appropriately spaced patterns, the magnitude and nature of shape fluctuations in the line/space patterns can be characterized using scanning probe techniques. In figure 8, C-AFM reveals a fluctuation in shape which includes significant line height and sidewall roughness in addition to the programmed line width roughness.[7] A scan along the line center reveals that this line height fluctuation has both periodic and uncorrelated components that appear to track the line width roughness measured by CD-SEM. Given that the ratio method outlined above is a ratio of intensities, and the intensity of the satellite peak is proportional to the total fluctuation in line shape, the value of LWR obtained from CD-SAXS is expected to be measurably larger than the value of line width roughness measured by the top-down imaging of CD-SEM. By the same logic, the Debye-Waller method of extracting LWR will include the additional periodic and uncorrelated roughness. The data in figure 8 suggest the disparity of LWR values in figure 7 are likely the result of comparing a technique that emphasizes line shape fluctuations with a technique that emphasizes line width fluctuations. Finally, we note that in resists and other structures where line height and sidewall angle fluctuations are small relative to the line width and line edge roughness, the two techniques are expected to provide quantitatively similar values. Future work will attempt to address this limit in sub-50 nm structures.

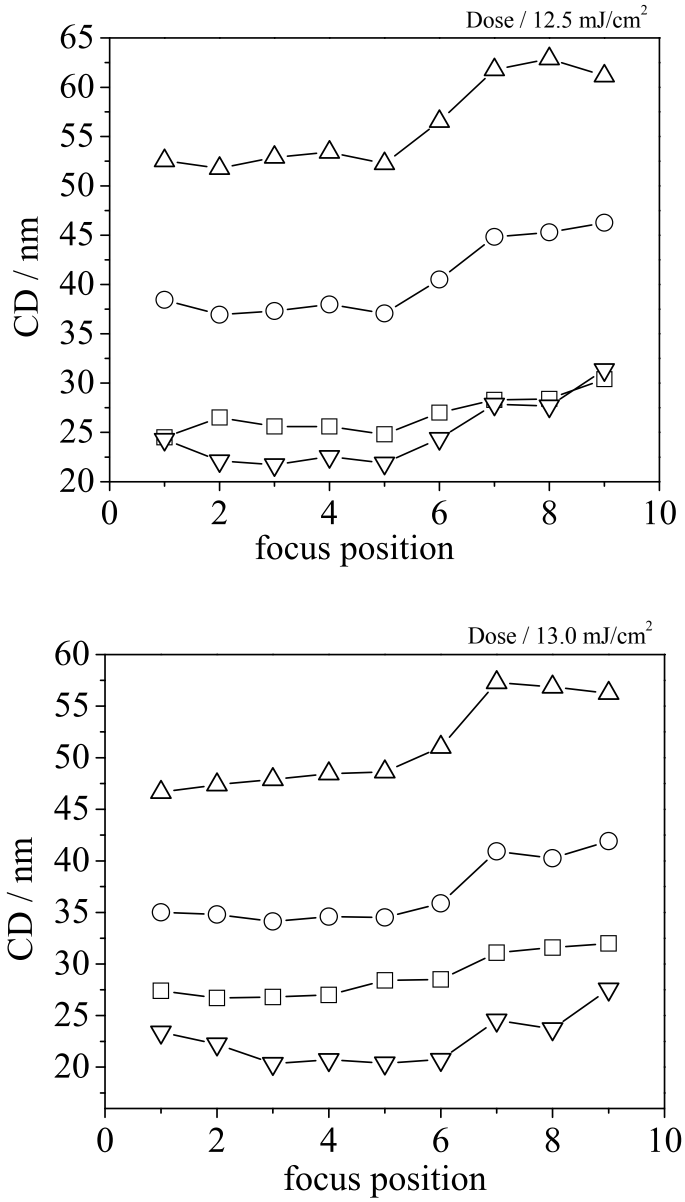


Fig. 6. Critical dimension (CD) is plotted as a function of sample number within two series of degrees of focus. Focus is increasing with sample number. Data are shown for two levels of dose, namely 12.5 mJ/cm$^2$ (top) and 13.0 mJ/cm$^2$ (bottom). Shown are three measures for each sample provided by CD-SEM, namely the top line width (down-triangles), bottom line width (up-triangles), and the average of the top and bottom line width (circles). CD-SAXS measurements, representing the average line width, are also shown (squares). The lines are drawn to guide the reader's eyes.

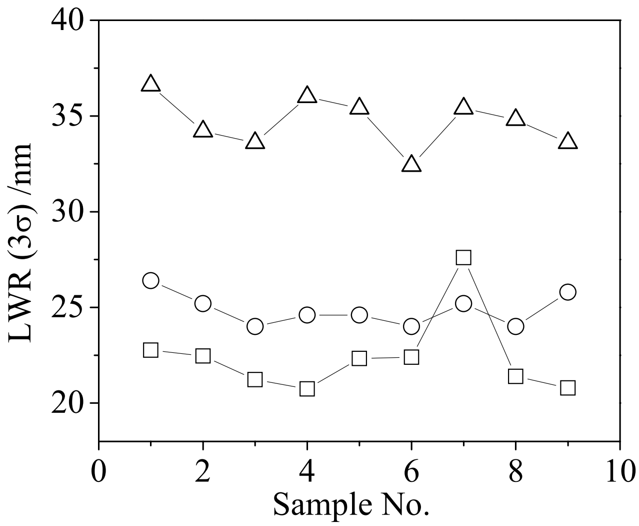


Fig. 7. Line width roughness (LWR) plotted as a function of sample number for a series of samples of varying focus measured by CD-SEM and CD-SAXS. Shown are data from two methods of LWR calculation from CD-SAXS, namely the ratio method described in the text (circles) and the effective Debye-Waller method (triangles). Also shown are the analogous values obtained from CD-SEM (squares). The lines are drawn to guide the reader's eyes.

## 4. CONCLUSIONS

In this report, the critical dimension and line width roughness of a series of EUV photoresist line/space patterns were measured by critical dimension small angle x-ray scattering (CD-SAXS) and compared to analogous results from critical dimension scanning electron microscopy (CD-SEM). CD-SAXS was found to be non-destructive to the e-beam sensitive photoresist patterns. The critical dimension, pitch, and LWR were found to be constant to within the uncertainty of the measurement after exposure to the x-ray beam for more than one hour, where a typical measurement is on the order of seconds. For a series of varying EUV focus exposures and two values of dose, the critical dimension measured by CD-SAXS, being a measure of the mass average of the line cross section, was consistently between the top and bottom CD measured by CD-SEM. However, there were significant differences observed between doses in the relative relationship between the average CD-SEM value of CD and the analogous value from CD-SAXS. This disparity is attributed to changes in the cross sectional shape of the patterns, which are approximated here as trapezoidal for the CD-SAXS measurements. These variations are also consistent with a similar disparity between the values of LWR measured by the two techniques, and further corroborated by calibrated AFM measurements of the line topology.

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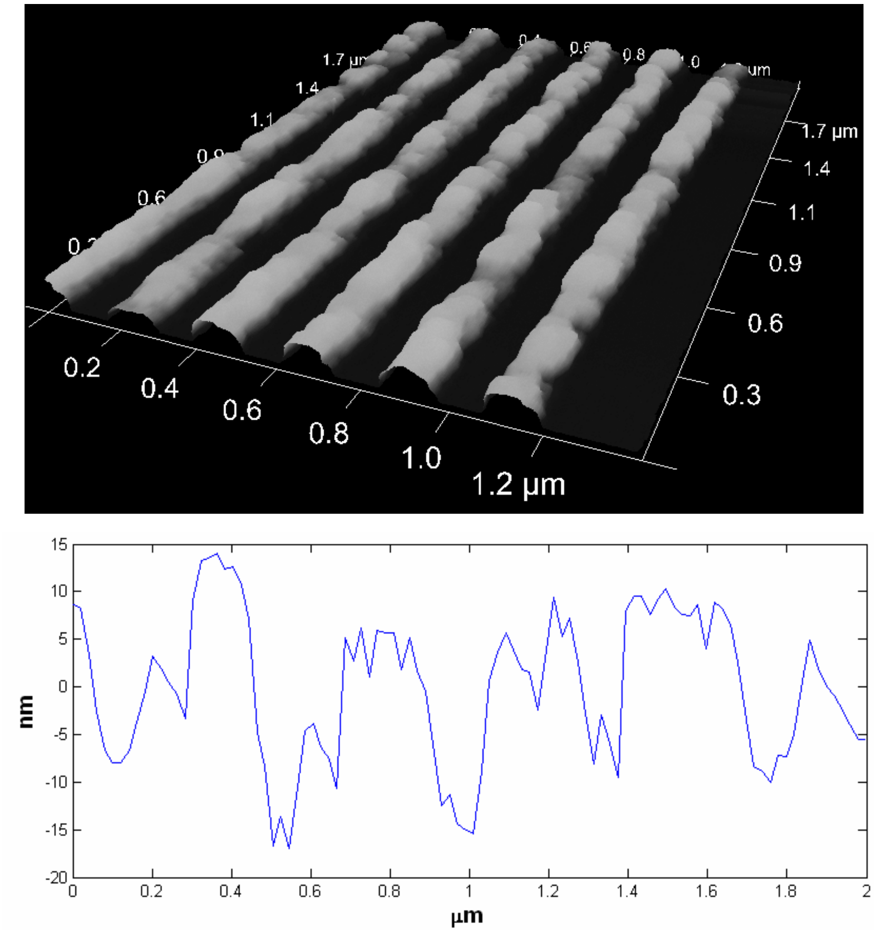


Fig. 8. Topography of one of the photoresist line/space patterns (top) as measured by calibrated atomic force microscopy (C-AFM). The image displays the magnitude of variation in shape fluctuation along the line direction, further demonstrated in the plot of height as a function of distance along a single line (bottom).

## REFERENCES

1. R. L. Jones, T. Hu, E. K. Lin, W.-L. Wu, R. Kolb, D. M. Casa, P. J. Bolton, G. G. Barclay, Appl. Phys. Lett. 83, 4059 (2003).
2. T. Hu, R. L. Jones, W.-L. Wu, E. K. Lin, Q. Lin, D. Keane, S. Weigand, J. P. Quintana, J. Appl. Phys. 96, 83 (2004).
3. R. L. Jones, T. Hu, C. L. Soles, E. K. Lin, W.-L. Wu, D. M. Casa, A. Mahorowala, Proc. SPIE 5375, 191 (2004).
4. R. L. Jones, W.-L. Wu, C-Q Wang, E. K. Lin, K.-W Choi, B. J. Rice, G. M. Thompson, S. J. Weigand, D. T. Keane, Proc. SPIE 6152, 61520N (2006).
5. C. Wang, R. L. Jones, E. K. Lin, W.-L. Wu, *submitted to Appl. Phys. Lett. (2007).*
6. Bunday, B., McCormack, D., Bishop, M., Villarrubia, J., Vladar, A., Dixson, R., Vorburger, T., Orji, N, and Allgair, J. "Determination of Optimal Parameters for CD-SEM Measurement of Line Edge Roughness". Proceedings of the SPIE: Metrology, Inspection, and Process Control for Microlithography XVIII (2004), 515-533.
7. N. G. Orji, R. G. Dixson, A. Martinez, B. D. Bunday, J. A. Allgair, T. V. Vorburger "Progress on Implementation of a CD-AFM-Based Reference Measurement System," Journal of Micro/Nanolithography, MEMS and MOEMS, accepted for publication.