Advanced Edge Roughness Measurement Application for Mask Metrology

D.Chase, R.Kris, R.Katz, A.Tam, L.Gershtein, R, Falah, N.Wertsman
Applied Materials Israel, 9 Oppenheimer, Rehovot 76705, Israel
Roman Liebe, Advanced Mask Technology Center GmbH &Co
Rahnitzer Allee 9, D-01109, Dresden, Germany

Abstract

Mask Manufacturers are continuously asked to supply reticles with reduced CD (Critical Dimension) specification, such as CD Uniformity and Mean to target. To meet this on-going trend the industry is in a quest for higher resolution metrology tools, which in-turn drives the use of SEM metrology into standard mask manufacturing process. As dimensions of integrated circuit features reduce, the negative effects of roughness of the features, and/or of components such as photo-resist and ancillary structures used to produce the features, become more pronounced since there is no corresponding reduction of roughness with dimension reduction. As a result of the increased problems, metrics that quantify roughness of specific sections of an integrated circuit have been developed; for example, line edge roughness (LER) measures the roughness of a linear edge.
This paper concentrates on one specific area of the Mask Metrology, being measurement of the different Roughness metrics of the reticle features such as lines and contacts, using a new SEM metrology tool, the Applied RETicleSEM. We describe the comprehensive Roughness Analysis Algorithm package that performs precise measurements of the different Roughness metrics including Fourier analysis, auto-correlation function and correlation length. This package can be used to isolate and characterize the roughness of specific wavelength ranges that may be of interest for mask manufacturing process and/or mask quality control considerations. We conclude with sample results of Roughness Analysis on real SEM images of Reticle lines. The influence of CD roughness on the precision of measurements is considered. The prove that long-wave roughness can be one from the sources of flyers during CD measurements is presented.

Key words: SEM Metrology, Mask Metrology, Roughness Measurements

1. INTRODUCTION

In this study, we describe the influence of line edge roughness over CD measurement. In Sec. 2 we discuss the relationship between CD measurement and the corresponding line edge roughness measurement. We address the question of how measurement box vertical shifts find expression in the measured CD results, focusing on the contribution of the CD roughness to the measurement precision.

2. HARMONIC MODEL OF LINE EDGE ROUGHNESS

We consider a simple harmonic model of the edge roughness (Figure 1). We represent the line as consisting of two continuous edges; both edges having the same characteristic harmonic wavelength, λ. The edges are phase-shifted by a phase shift $\Delta\varphi$ given by $\Delta\varphi = \varphi_1 - \varphi_2$ where sub indices denote the first and second edges.

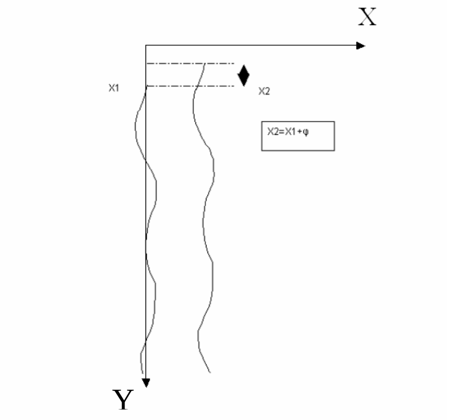

Figure 1. Harmonic model of Line Edge Roughness

The actual edge location X_i is given as function of the height y , by the following equation:

$$X_i = X_i^{\,0} + A\sin(2\pi\frac{y}{\lambda} + \varphi_i) \qquad (1),$$

Where X_i is the edge location of edge i at a given y . $X_i^{\,0}$ is the average edge location of edge i. *A* is the amplitude. λ is the characteristic wavelength and φ_i is the phase of edge *i*.

The model can be correlated to a real example where the characteristic wavelength, λ, will be given by the PSD maximum when there exists a dominent. wavelength for the measured edge. The measurement is restricted by inherent limitation to a measurement box (MeasBox) of size L . The MeasBox size defines the upper bound for the maximum wavelength value that can be measured. Similarly, the pixel size defines the lower bound for the minimal wavelength value. In this treatment, the wavelength is considered to be large enough such that the pixel size is not a limiting factor.

The average edge location in the MeasBox is estimated by integration over the model in length of MeasBox size:

$$< X_i > = \frac{1}{L}\int_{Y_1}^{Y_1+L} (X_i^0 + A\sin(2\pi\frac{y'}{\lambda} + \varphi_i))dy' \qquad (2).$$

Lets indicate X_1, X_2 as the model for the left and the right edge respectively. We perform the above calculation for both sides of the measured edge. After simple calculation we get from Equation (2):

$$< X_1 > = X_1^0 + \frac{A}{\pi}\frac{\lambda}{L}\sin(2\pi(\frac{Y_1}{\lambda} + \frac{L}{2\lambda}) + \varphi_1)\sin(\frac{\pi L}{\lambda})$$
$$< X_2 > = X_2^0 + \frac{A}{\pi}\frac{\lambda}{L}\sin(2\pi(\frac{Y_1}{\lambda} + \frac{L}{2\lambda}) + \varphi_2)\sin(\frac{\pi L}{\lambda}),$$

where $< X_1 >$, $< X_2 >$ are the average locations of the left and right edges.

By using the above description for the average edge location of the left and the right edge, we obtain the line width (CD) defined by the distance between them. This described by the following relation:

$$CD = \left| < X_1 > - < X_2 > \right| = CD^0 + \frac{A}{\pi}\frac{\lambda}{L}\sin(\frac{\pi L}{\lambda})\cdot\left[\sin(2\pi(\frac{Y_1}{\lambda}+\frac{L}{2\lambda})+\varphi_1) - \sin(2\pi(\frac{Y_1}{\lambda}+\frac{L}{2\lambda})+\varphi_2)\right] =$$

$$= CD^0 + 2\frac{A}{\pi}\frac{\lambda}{L}\sin(\frac{\pi L}{\lambda})\cos(2\pi(\frac{Y_1}{\lambda}+\frac{L}{2\lambda})+\frac{\varphi_1+\varphi_2}{2})\sin(\frac{\varphi_1-\varphi_2}{2}) =$$

$$= CD^0 + 2\frac{A}{\pi}\frac{\lambda}{L}\sin(\frac{\pi L}{\lambda})\cos(2\pi(\frac{Y_1}{\lambda}+\frac{L}{2\lambda})+\frac{\varphi_1+\varphi_2}{2})\sin(\frac{\Delta\varphi}{2})$$

As can be seen in the CD definition, there are 2 components that play a role in the CD measurement results:
CD^0 - the distance between the averages left and right edge location.
The second component depends on the main wavelength and the shift of the edges in respect to one another. This component is donated by the roughness of the edge and the MeasBox location.
Now we can estimate the roughness influence on CD measurement as:

$$\Delta CD = 2\frac{A}{\pi}\frac{\lambda}{L}\sin(\frac{\pi L}{\lambda})\cos(2\pi(\frac{Y_1}{\lambda}+\frac{L}{2\lambda})+\frac{\varphi_1+\varphi_2}{2})\sin(\frac{\Delta\varphi}{2}) \le 2\frac{A}{\pi}\frac{\lambda}{L}$$

The formula above is based on the assumption that both edges have the same spatial frequency as stated before.
We learn that both roughness amplitude and the dominant wavelength to MeasBox size ratio has significant contribution to the variability of the CD measurement result. Pin pointing the roughness amplitude and the dominant wavelength enable us better understanding and predict the roughness contribution to CD changes.
We would like to point out that the shift in the edge location in the Y direction contributes to the ΔCD measured by increasing the roughness contribution to the measured CD when the shift is in the dimensions of half wavelength size.

3. LER STUDY OF THE AMTC RETICAL IMAGE

We performed the LER (Line Edge Roughness) study of the AMTC image of the isolated line (Figure 2) origin in AMTC mask.

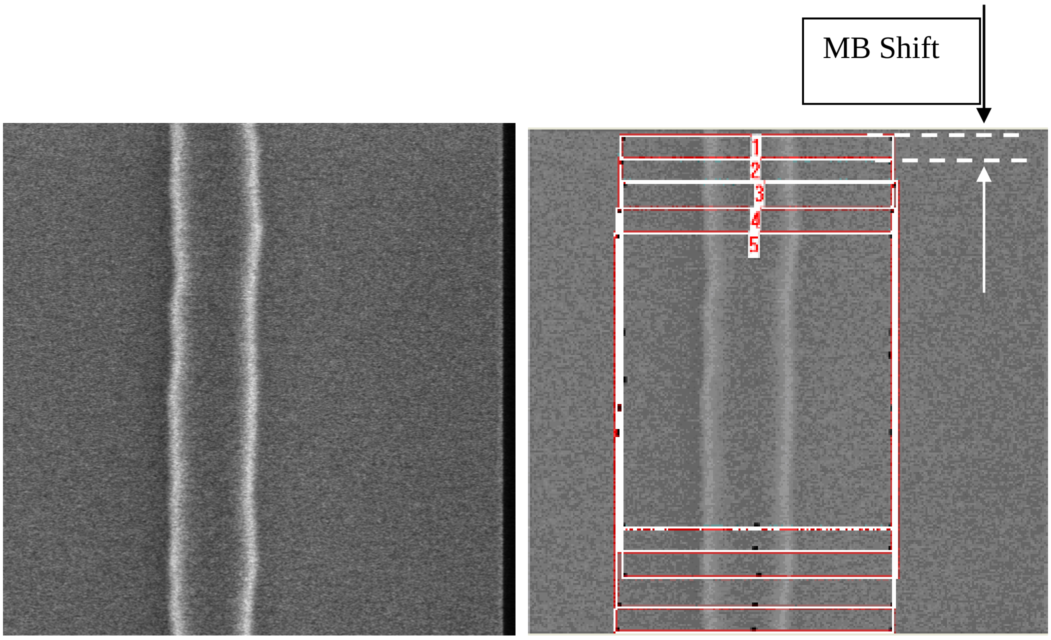

Figure 2a,b. AMTC line. Modeling of Meas Box location shift with Multi ROI

3.1 Experiment description

We performed Edge roughness analysis for the given edge in the above image. The result of Edge roughness analysis for the above image is 8.7 nm. The roughness result stands for the 3 Sigma of the deviation of the measured CD from straight line fit of the feature's edge.

For a simple harmonic line model, the amplitude of main wavelength can be estimated as half of the 3 Sigma. This way we estimate the amplitude of the harmonic perturbation as A ≈ 4 nm.

We extract the Power Spectrum (PSD) of the measured line (Figure 3).

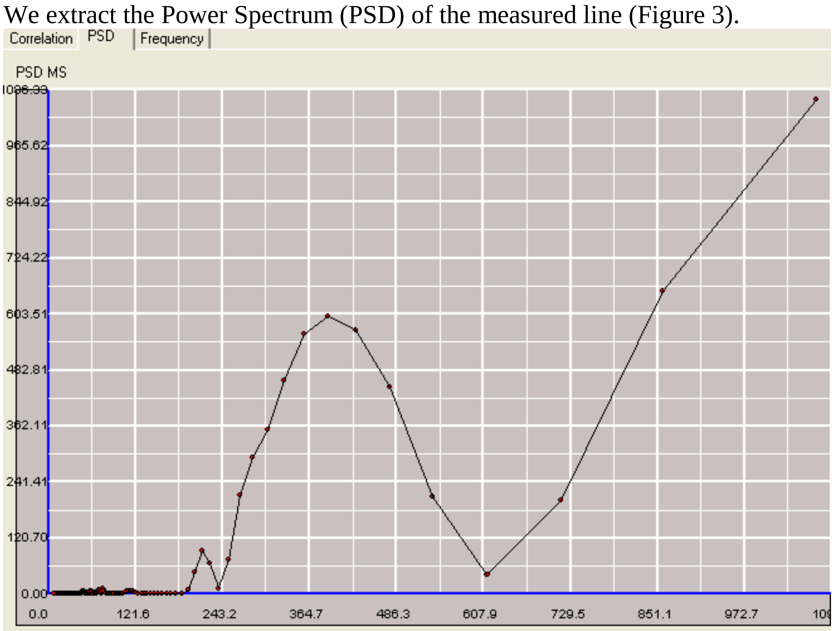

Figure 3. Roughness PSD of the measured edge from Figure 2.

Using the PSD graph, we extract the significant wavelength. It can be seen from the PSD plot(Figure 3) that the main wavelength for this measurement can be estimated as $\lambda \approx 400$ nm. The size of the measurement box that was used in this measurement is 1[μm]. Combining the above information regarding the roughness amplitude, main wavelength and measurement box size, we estimate that the expected CD variation (ΔCD) is as follows:

$$\Delta CD \le 2\frac{A}{\pi}\frac{\lambda}{L} = \frac{2}{\pi}\cdot 4\cdot\frac{400}{1000} \cong 1[nm]$$

We conducted several measurements taken on the same line. Each measurement used the same algorithm arameters and differed from one another by the vertical shift in Y direction of the MeasBox location. By using several measurement boxes shifted from one another, we asked to study about the contribution of the roughness to the CD precision given by the shifted boxes. Since all measurement box measures the same line, we expected to get variability donated by the roughness of the edge.
We repeated the test for several shifts in the MeasBox location in order to point out the relation between the measurement box shift and the CD result. These shifts are simulating different MeasBox location variation within measurement sets donated by PR arrival that effect measurement box placement.
For each set of measurement constant shifts, the 3Sigma of the CD was calculated.

3.2 Experiment results
Figure 4 describes the connection between the MeasBox shift and the 3 Sigma measured.
Each point represents 3 Sigma of CD result from 5 measurements with fixed MeasBox shift (as on Figure 2b).
As can be seen from the graph below, as the MB shift increases, the 3 Sigma increases as well. It can be seen that when increasing the shift the 3 Sigma value draw near the estimated ΔCD value. This result emphasis the relation between the 3 Sigma and the roughness contribution.

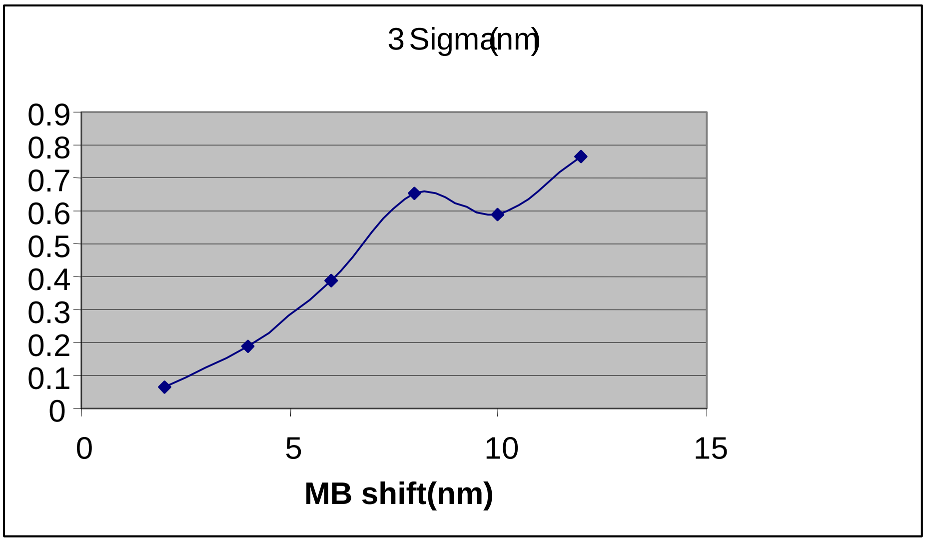

Figure 4. Precision dependence on MeasBoxPlacement (MB shift).

In figure 5, we show the average CD dependence on the MeasBox placement. Every point represents average CD result of 5 measurements with fixed MeasBox shift. It can be seen that as the MeasBox shift increases, the average CD decreases. We learn from this relationship that larger CD variation leads to smaller average CD (due to shifts around the average value). We would like to point out the CD average value decreased in 0.15% of the total CD. This means that the average value has only slightly changes.

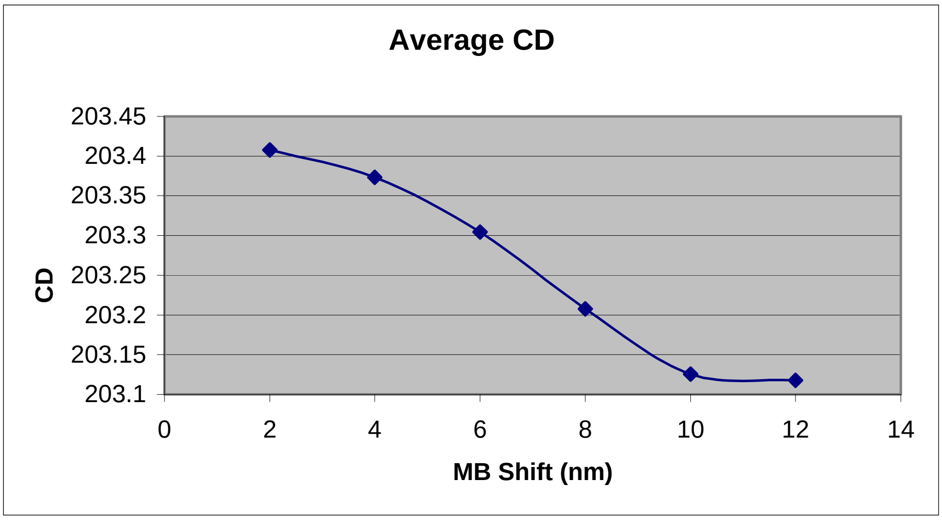

Figure 5. Average CD dependence on MeasBox Placement (MB shift).

4. SUMMARY AND CONCLUSIONS

We modeled the line edge roughness by a simple harmonic model. This model assumes the same dominant wavelength for both line edges (right and left).

We conducted line edge roughness analysis that included PSD and 3 Sigma calculations. We estimated the upper bound for the roughness impact on CD precision. We simulate the influence of longwave roughness on CD precision measurements.