Advanced Edge Roughness Measurement Application for Mask Metrology

Thomas Marschner[*a], Jan Richter[a], Uwe Dersch[a], Amit Moran[b], David Chase[b], Ruty Katz[b], Reuven Falah[b], Thomas Coleman[b]
[a]Advanced Mask Technology Center (AMTC), Raehnitzer Allee 9, D-01109 Dresden, Germany;
[b]Applied Materials Israel, 9 Oppenheimer, Rehovot 76705, Israel

ABSTRACT

With decreasing C qD dimensions the negative influence of line edge roughness (LER) and linewidth roughness (LWR) on CD uniformity and mean-to-target CD becomes more pronounced, since there is no corresponding reduction of roughness with dimension reduction. This applies to wafer metrology as well as to mask metrology. In order to better understand the types of roughness as well as the impact of the CD-SEM roughness measurement capabilities on the control of the mask process, the sensitivity and accuracy of the roughness analysis were qualified by comparing the measured mask roughness to the design for a dedicated LER test mask. This comparison is done for different LER amplitude and periodicity values and for reference structures without nominal LER using the built-in CD-SEM algorithms for LER characterization.

Key words: CD-SEM Metrology, Mask Metrology, LER, LWR

1. INTRODUCTION

Mask Manufacturers are continuously asked to supply reticles with tighter CD (Critical Dimension) specifications, such as CD uniformity (CDU) 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 due to litho and etch process on CDU and mean-to-target CD become more pronounced, since there is no corresponding reduction of roughness with dimension reduction.

As a result of the increased LER influence, metrics that quantify roughness of specific sections of an integrated circuit have been developed; for example, line edge roughness (LER) and line width roughness (LWR) measuring the roughness of a linear edge and of the CD values along the edge.

This paper continues previous efforts on the analysis of LER on wafer [1, 2] and reticle level [3, 4] to the field of mask metrology. In order to better understand the types of roughness as well as the impact of the CD-SEM roughness measurement capabilities on the control of the mask process, the sensitivity and accuracy of the roughness analysis were qualified by comparing the measured mask roughness to the design for a dedicated LER test mask.

SEM Roughness measurements are a developing area. A roughness pattern on a wafer can be formed by roughness on the mask, but as well by noise and process variations in litho and etch. In this work, we aspire to close a loop on the roughness manufacturing cycle. We designed a mask with artificial LER and LWR. The planted roughness varies in three parameters:

1. Amplitude.
2. Main period (wavelength).
3. Line CD.

The roughness patterns were designed both for horizontal and for vertical lines. In this paper, we are focusing on 300nm lines with varying roughness amplitudes and dominant wavelengths. We study the relationship between the designed LER to the roughness written on the mask.

2. EXPERIMENTAL

2.1 Mask Design

A dedicated test mask has been manufactured using a NuFlare EBM4000 e-beam mask writer with varying roughness patterns. In previous work, it has been proven that process induced line edge roughness is typically independent between both left and right edges and LWR can be directly calculated from the LER values of both edges [1]. For this reason, we investigated the roughness of the right and left line edges only and not the CD roughness. We base our work on the

*e-mail: Thomas.Marschner@amtc-dresden.com; phone +49 351 4048 207

design of fully correlated roughness patterns. For fully correlated line roughness, the right and left edges have the same shape and phase of roughness resulting in an expected zero CD roughness.

2.2 Analysis Procedure

All measurements were performed on an Applied Materials RETicleSEM system using the built-in algorithms to extract the LER values. For further analysis, all CD-SEM images were automatically stored. The analysis was based on (nominally) 300nm vertical and horizontal lines with different roughness amplitudes and dominant wavelengths.

Using a measurement box size of 10μm, we can investigate roughness defined by spatial periods of up to 4μm. We limit the analysis to this maximum wavelength since a minimum number of repetitions of the full period are required so that the measured roughness will be unbiased and the analysis will be of sufficient confidence. For all measurements 1000 scans along the measurement box have been used. This amounts to a spatial resolution of 10nm along the line.

In addition, we have measured structures without planted roughness for reference. This enables us to distinguish between planted roughness and process roughness. Process roughness may be formed by writer noise, vibrations in the tool, resist and etch process and SEM image acquisition added disturbances [5]. This will result in frequencies that do not depend on the original planted frequencies (i.e. not harmonics of the major frequency).

Table 1 shows a detailed description of periods and amplitudes of the measured data set.

Set	**Period [nm]**	**Amplitude [nm]**
1-2	4000	220, 50
3	3000	50
4	1000	100
5	500	50
6-8	200	200, 100, 50
9	140	50
10	100	50
11	Reference	

Table 1: Summary of period and amplitudes of the analyzed data set

To correlate the measurements to the designed planted roughness we have created artificial images containing the designed signal (i.e. a square wave with the required period and amplitude). We used the same measurement techniques to measure the roughness on these artificial signals as for the measurements done on the mask. We used these measurements as a reference for the theoretically expected roughness.

2.3 Comparison criteria

We chose to compare the roughness in the written lines on the mask using the following criteria:

1. Designed CD, amplitude and major period.
2. Compare the spectral image of the measured line to the expected spectrum.
3. Use the spectrum comparison to determine the transfer function between the designed and the printed roughness.

3. EXPERIMENT RESULTS

3.1 Design vs. printed roughness

3.1.1 Main period

We have compared the main period measured on the mask to the designed period of the planted roughness for a nominal amplitude of 50nm. The main period was calculated by taking the most significant peak of the Power Spectrum Density (PSD). The PSD is calculated as part of the roughness measurements. Table 2 summarizes the measured and designed periods. Figure 1 displays the results graphically. It can be seen that the main period measured is consistent with the designed one for all periods above 100 nm. A linear fit for the periods above 100nm shows a slope very close to unity.

The period measured on the designed 100 nm line is very close to the dominating period measured on the reference structure, although the intensity of this period is significantly lower than the intensity of the artificially planted periods. This indicates that for a periodicity of 100nm the limit of the used mask writer is approached. This result shows that such an artificial LER design can be additionally used for characterizing the limits of mask writing tools.

Design Period [nm]	Measured Period [nm]
4000	3892
3000	2883
1000	1017
500	509
200	201
140	139
100	1668
Reference	1820

Table 2: Main period measured on the mask compared to the designed LER period

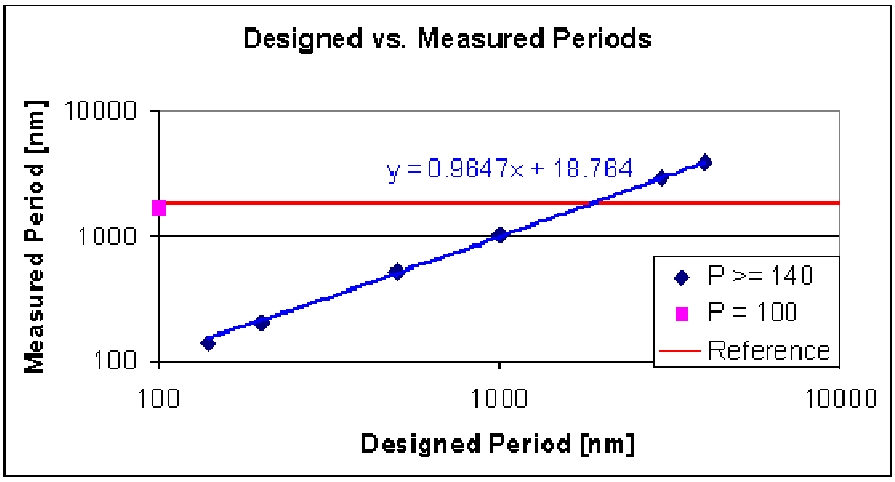

Figure 1: Main period measured on the mask compared to the designed period. The results for designed periods above 100 nm are marked in blue diamonds and a linear fit equation of the fit is shown. The period measured for the 100 nm design is marked by a purple square while the measured period on the reference structure is marked by the red horizontal line.

3.1.2 Amplitude

The measured roughness amplitudes were compared to the designed ones. Because the lines taken from the mask SEM image were exactly vertical a linear fit was applied to the edge and the amplitude was calculated from the residuals. Figure 2 shows this procedure graphically. The precision of LER amplitude measurement has been determined before to be below 1nm (3 sigma) [1]. Therefore, the influence of tool precision can be neglected for the LER amplitude values investigated in this work.

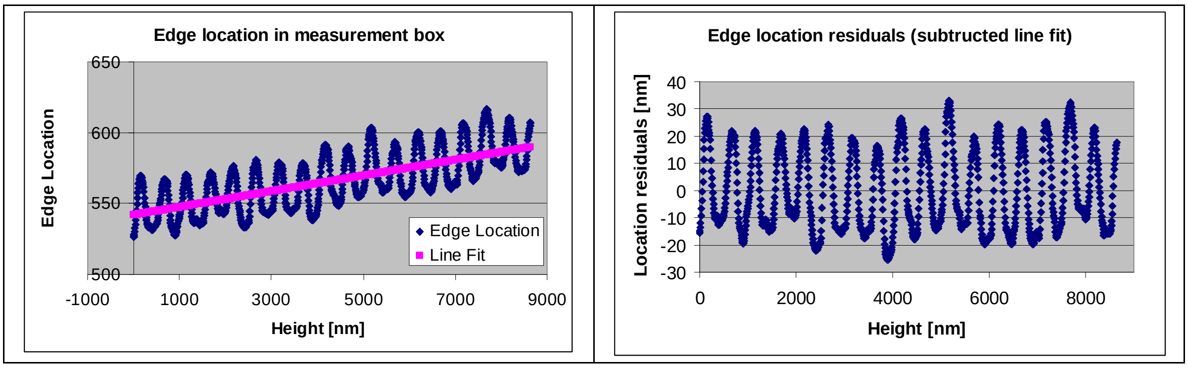

Figure 2: Edge location in the measurement box and their residuals after subtracting a linear fit.

Table 3 summarizes the measured amplitudes and Figure 3 displays them graphically. For planted roughness with periods between 500 and 4000nm the measurement roughness is in agreement with the designed one. The curve comparing these amplitudes to the designed one is fitted by a line with a slope close to unity. For planted roughness with periods lower than 500 nm the measured amplitudes are only 40 – 50 % of the designed ones. The curve comparing these amplitudes to the designed one is fitted by a line with a slope of 0.43. The amplitude measured on the reference structure is around 20nm.

Period [nm]	**Design Amplitude [nm]**	**Measured Amplitude [nm]**
4000	220	234
3000	50	50
1000	100	98
500	50	58
200	200	82
200	100	49
200	50	29
140	50	13
100	50	12
Reference		19

Table 3: Amplitudes measured on the mask compared to the designed amplitudes.

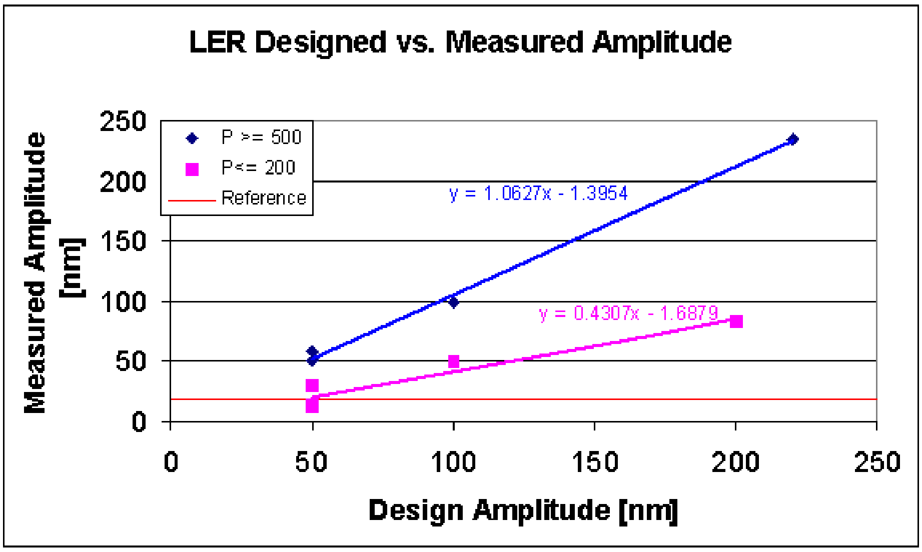

Figure 3: Amplitudes measured on mask compared to designed amplitudes. Amplitudes for signals with periods greater or equal to 500 nm are marked in blue diamonds. Amplitudes for periods smaller than 500 nm are marked in purple squares. For both curves a linear fit with its equation is shown. The amplitude measured on the reference structure is marked by the horizontal red line.

3.2 Spectral comparison

3.2.1 Main Period

The Power Spectrum Density (PSD) of planted roughness was compared to the one of the design for different amplitude and phase values. The PSD of the design is a classical square-wave spectrum consisting of many harmonics of the major period. Figure 4 illustrates the difference between the designed and mask signals and the resulting PSD.

The comparison of the mask PSD to the design PSD shows that there is a major attenuation of the PSD as we go to lower frequencies (or higher wave-lengths). For wave-lengths lower than about 40 nm (or frequencies higher than 0.025/nm) we see almost no power at all (see Figure 4). In our measurements this limit is in the order of around 4 pixels. This may imply that the attenuation is affected by the measurement resolution.

Figure 5 summarizes the PSD for all measured designed periods as well as for the reference structure without planted LER. It can be seen that for long periods (4000 and 3000nm), the PSD of the mask follows the one of the design very closely. As we go to lower periods (1000 and 500nm), the PSD of the mask starts to differ from the one of the design after several harmonics of the major periods. For even lower periods (200 and 140 nm) the PSD of the mask agrees with the one of the design only for the major frequency. In this regime, lower frequencies start to dominate the spectrum although the major peak is still the same one as designed. For the lowest period measured (100 nm) we see no correlation between the PSD of the mask and the PSD of the design. As was discussed in Section 3.1.1, the PSD of the mask shows no strong peak in 100 nm but only lower frequency contributions due to the mask writer resolution limit.

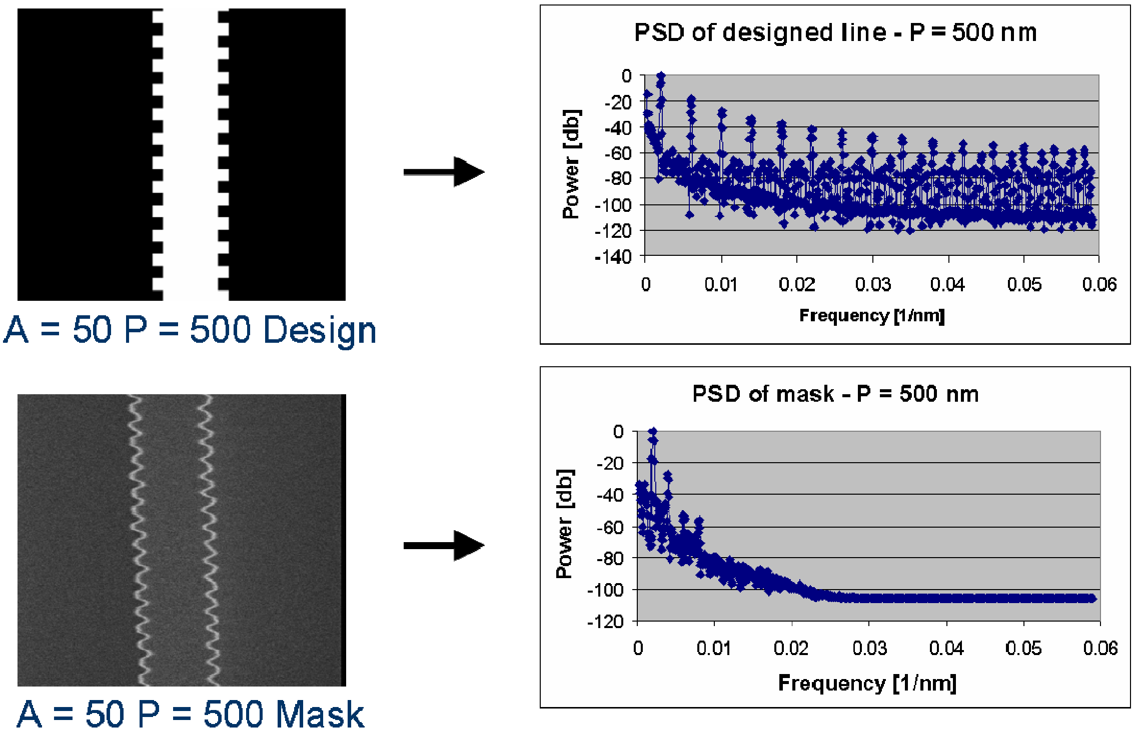

Figure 4: Power Spectrum Densities of design line (upper panels) and mask (lower panels). The PSD of a designed square–wave consists of repeating harmonics of the major frequency.

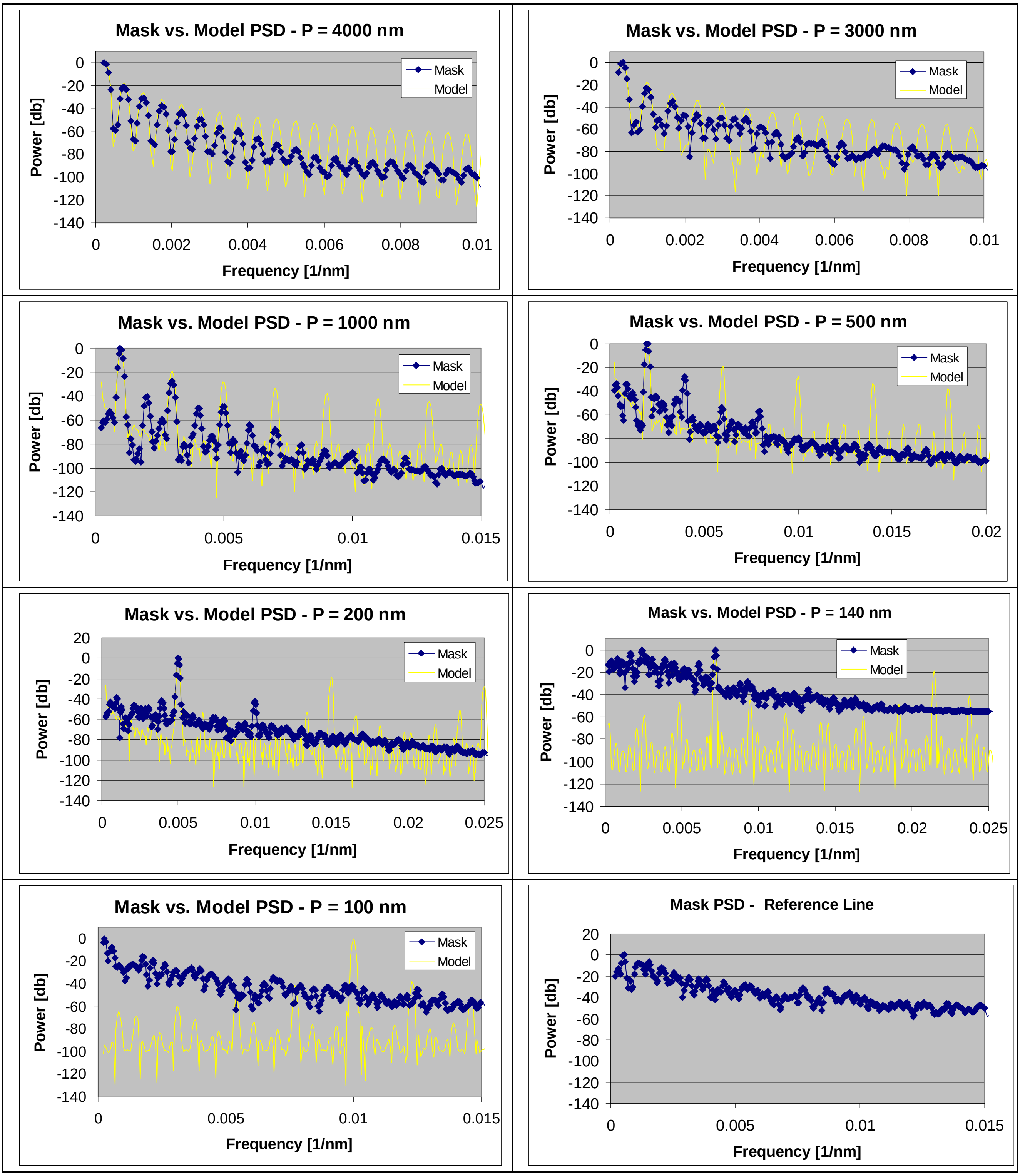

Figure 5: PSD of masks compared to the design. Panels show from top left to lower right planted roughness with an amplitude of 50nm and periods of 4000, 3000, 1000, 500, 200, 140 and 100 nm and the reference structure.

3.2.2 Independent Periods

We define "independent" periods as ones which are not related to the main period of the planted roughness. Such periods can arise from process roughness and can represent e.g. a property of the writing system. To search for such periods we used two complementary ways: measure the roughness of the reference structure and measure the roughness of the straight line section of the long period planted roughness.

The PSD of the reference structure shows several series of periods and their harmonics. **Error! Reference source not found.** summarizes the main periods found in the PSD of the left and right edges of the vertical reference structure and their lowest visible harmonics. The left and right edge PSD main periods differ from each other. However, a period of around 280 nm is present for both edges (285 nm in left edge and the 16^{th} harmonic of the 4450nm period in the right edge).

Left Edge		Right Edge	
Major Period [nm]	**Visible harmonics Number**	**Major Period [nm]**	**Visible harmonics number**
2860	1, 3, 4, 6	4450	1, 3, 5, 6, 8, 9 …
1334	1, 4,	425	1, 2, 3
285	1, 2		

Table 4: Main periods and their harmonics found on the PSD of the vertical reference structure. Both left and right edges results are shown.

We searched for these periods in the planted roughness sample as well. We found a period of 280 nm in both the 1000 and 500 nm period signals as shown in Figure 6. In the 200 and 140 nm signals we found a process period of 410 nm corresponding to the 7^{th} harmonic of the 2860 nm period as depicted in Figure 7. The edges with the planted roughness of 200 and 100 nm did not show a process period of 280 nm. We proceeded to calculate the PSD for the Line Width Roughness (LWR) between the left and right edges of these periods. In both PSD spectra a period of 140 nm was observed (see Figure 8). The 280 nm period was also identified in the PSD measured on the straight section of the long (4000 and 3000 nm) planted roughness structures. Figure 9 shows the PSD for both signals.

Additionally we compared the process roughness difference between horizontal and vertical lines. We measured the roughness on a vertical and horizontal reference structures. Table 5 summarizes the roughness properties for both structures. It can be seen that the period of 280 nm is present in both structures.

This indicates that this additional periodicity is not caused by the mask writer, but by other process or measurement influences. To find the origin of this additional periodicity needs further investigations.

	Vertical		Horizontal	
	Left	**Right**	**Left**	**Right**
Amplitude [nm]	19	16	20	18
Main Period [nm]	2860	4450	1820	1540
2^{nd} Period [nm]	1334	425	645	950
3^{rd} Period [nm]	285		280	290

Table 5: Comparison of roughness properties for vertical and horizontal reference structure.

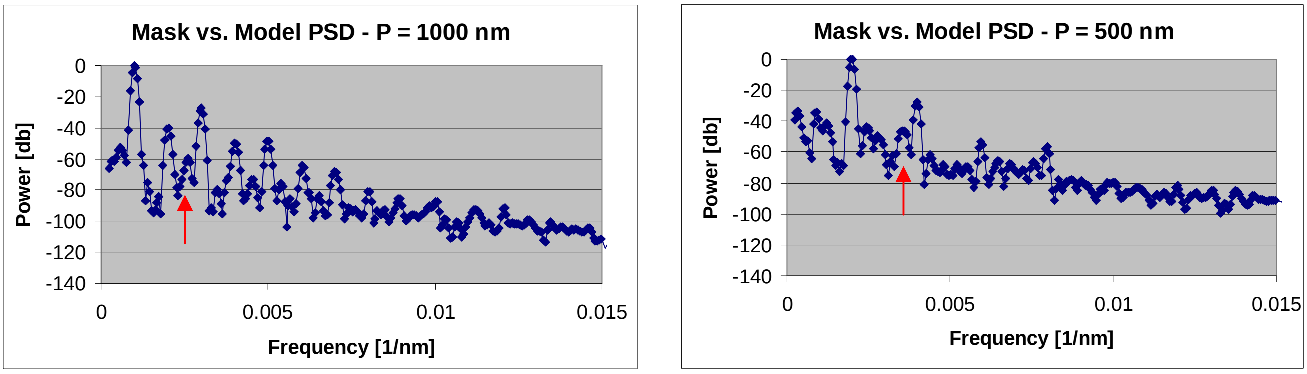

Figure 6: Process period of planted roughness signals – The process period of 280 nm is marked by the red arrow.

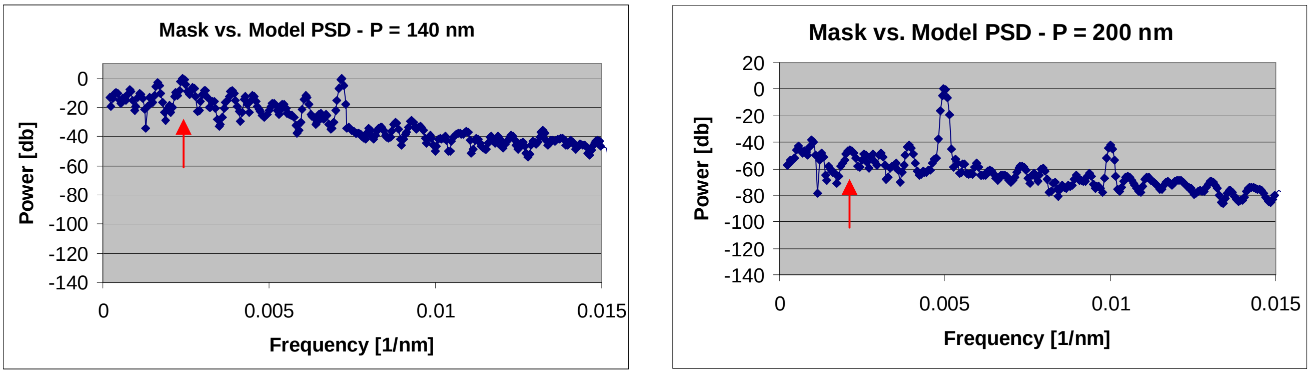

Figure 7: Process period of planted roughness signals – The process period of 410 nm is marked by the red arrow.

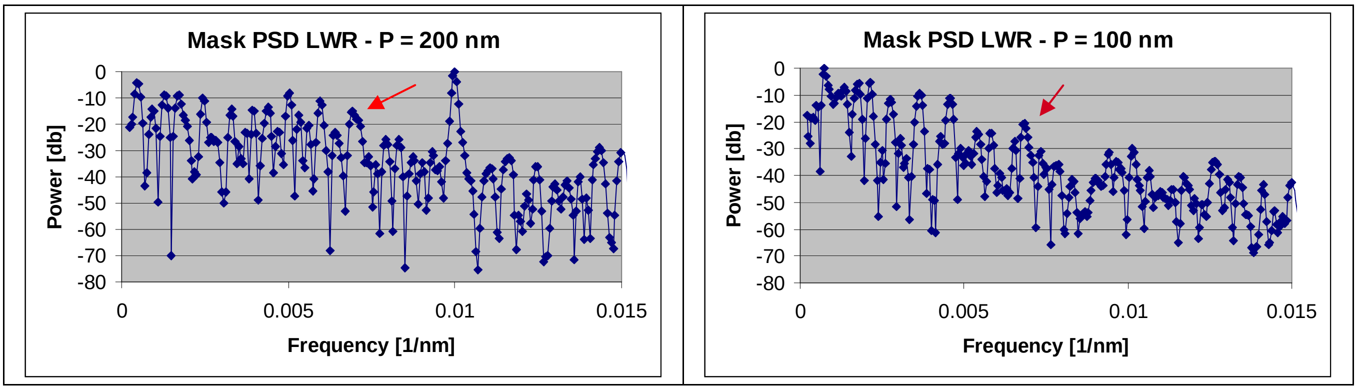

Figure 8: LWR PSD of planted roughness of 200 and 100 nm. The process period of 140 nm is marked by the red arrow.

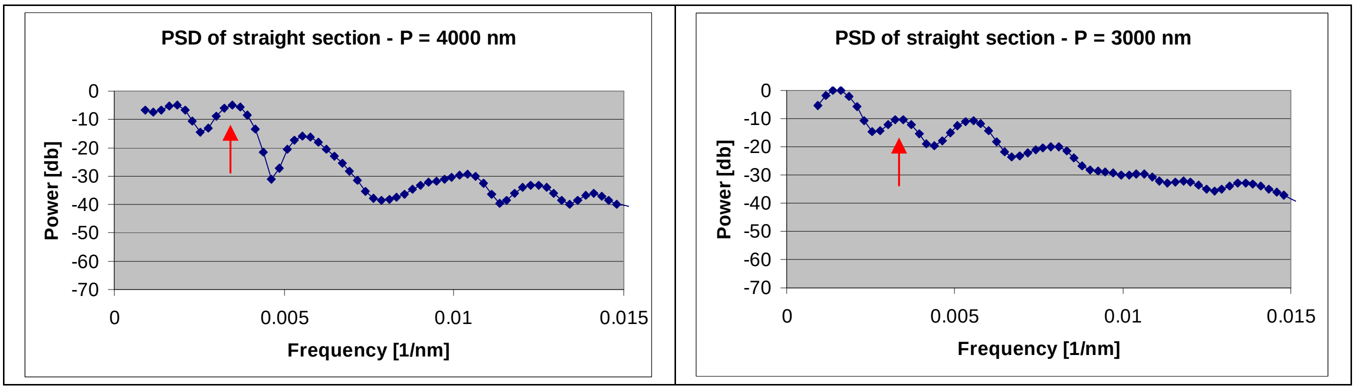

Figure 9: PSD of the straight line section of the planted roughness lines. The red arrow marks the P = 280 nm process period.

4. SUMMARY AND OUTLOOK

CD-SEM measurements on a mask with planted LER of different amplitudes and periodicities were compared to the design. Roughness measurements showed that the major period designed was evident on the mask down to a period of 140 nm. As the period goes down the printed roughness diverges from the designed one. For very low periods below 100 nm the printed roughness is not correlated the design anymore indicating the limits of the mask writing process. Amplitudes of printed lines agree with the design down to a period of 500nm. Below that amplitudes are damped to about 40% of their designed value. Additional process roughness not related to the planted roughness has been identified. The process roughness periods are composed of long periods (larger than 2000 nm) and short periods. The long periods differ between left and right edges and between horizontal and vertical structures. A unique period of 280 nm was identified through all reference structures and in many of the planted roughness images.
For a better understanding of the impact of the generated mask roughness on the final printed wafer also aerial image simulations both of the original CAD design and of the Mask SEM contours have to be carried out to estimate the CAD to Mask transfer effects. A final step will be to print wafers using the specially designed mask and to measure the roughness on the wafer. From this, the final LER transfer function from design to reticel to aerial image to wafer can be determined.

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