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Event: SPIE Advanced Lithography, 2018, San Jose, California, United States

Setting up a proper Power Spectral Density (PSD) and Autocorrelation Analysis for Material and Process Characterization.

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ABSTRACT

Power spectral density (PSD) analysis is playing more and more a critical role in the understanding of line-edge roughness (LER) and linewidth roughness (LWR) in a variety of applications across the industry. It is an essential step to get an unbiased LWR estimate, as well as an extremely useful tool for process and material characterization. However, PSD estimate can be affected by both random to systematic artifacts caused by image acquisition and measurement settings, which could irremediably alter its information content.

In this paper, we report on the impact of various setting parameters (smoothing image processing filters, pixel size, and SEM noise levels) on the PSD estimate. We discuss also the use of PSD analysis tool in a variety of cases. Looking beyond the basic roughness estimate, we use PSD and autocorrelation analysis to characterize resist blur [1], as well as low and high frequency roughness contents, applying this technique to guide the EUV material stack selection. Our results clearly indicate that, if properly used, PSD methodology is a very sensitive tool to investigate material and process variations

Keywords: Line-edge roughness, Line-width roughness, power spectral density, autocorrelation coefficient, PSD, LER, LWR.

1. INTRODUCTION

In the last years, the importance of Power Spectral Density (PSD) in characterizing roughens has become crucial. In the next chapters of this paper, we report how different process steps (lithography / etch) can show a different impact on the PSD curves, especially with respect to SEM noise. In Section 2 we specifically investigate this aspect to understand how to standardize our measurement approach and, consequently, our way of looking at PSD.

In Section 3, we focus on the impact of underlayer on roughness for 16 nm CD dense EUV lines of. We also study the impact of different underlayers on CD-SEM image noise and on the PSD curves.

In the Section 4, we investigate how etch smoothening process changes the PSD curves and we discuss in detail what is the roughness improvement provided by this process.

To better understand the terminology used in this paper, regarding the PSD three-parameters model , a schematic example of a PSD curve is shown in Figure 1.

Metrology, Inspection, and Process Control for Microlithography XXXII, edited
by Vladimir A. Ukraintsev, Ofer Adan, Proc. of SPIE Vol. 10585, 105851K
· doi: 10.1117/12.2297264

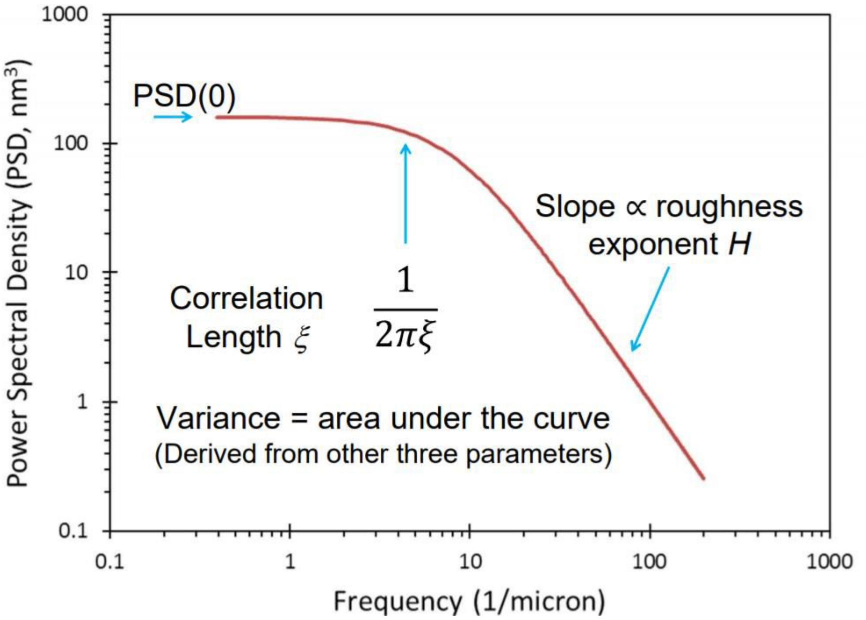

Figure 1: Example of a typical power spectral density

Here the term PSD (0) indicate the zero-frequency value of the PSD, which can never be directly measured but can be thought as the asymptotic value of the PSD in the low-frequency region. It describes the edge variations occurring over large-scale lengths. In the low-frequency region, the PSD is flat and then, once reached a certain critical frequency, it falls off as a frequency power-low. We usually refer to this region as high-frequency domain, describing the edge variations over short-scale lengths. The separation between these two regions is marked by the correlations length ξ,marking the transition between uncorrelated and correlated behavior. The power law of the PSD curve in the high-frequency domain is characterized by Hurst exponent H.

These three parameters (PSD (0), ξ, H) are sufficient to fully describe line edge roughness (LER) and line width roughness (LWR)

2. PSD SETUP

2.1 The SEM noise impact on the PSD

This section has the scope to describe how to set up an appropriate PSD analysis. Once this is properly done, we will be able to better understand and characterize roughness for the features being investigated.

We stress the importance of having a roughness measurement independent of the SEM noise. As reported [2], this can be achieved by subtracting the SEM noise in Fourier space.

This procedure is illustrated in Figure. 2. The biased PSD obtained from a SEM image is dominated by the SEM noise in the high-frequency regime. In case of white noise, the PSD is flat in the high-frequency regime, where the measured PSD is dominated by the image noise and not actual feature roughness. Un-biasing basically consist in subtracting the noise component by the PSD curve.

For after-etch images, we observe that the SEM noise is about one order of magnitude lower compared to the after-litho case. This is understandable, as images of resist lines are usually acquired with lower frames averaging and landing voltage. Therefore, the noise contribution will be larger if compared after-etch.

Historically, the comparison of roughness after litho and after etch has been interpreted as indicating that the improvement was dominated by the smoothening induced while transferring the pattern, thus leaving small room for lithography improvement. Hence, un-biasing is critical to correctly understand the smoothening of different treatment, from exposure to etch.

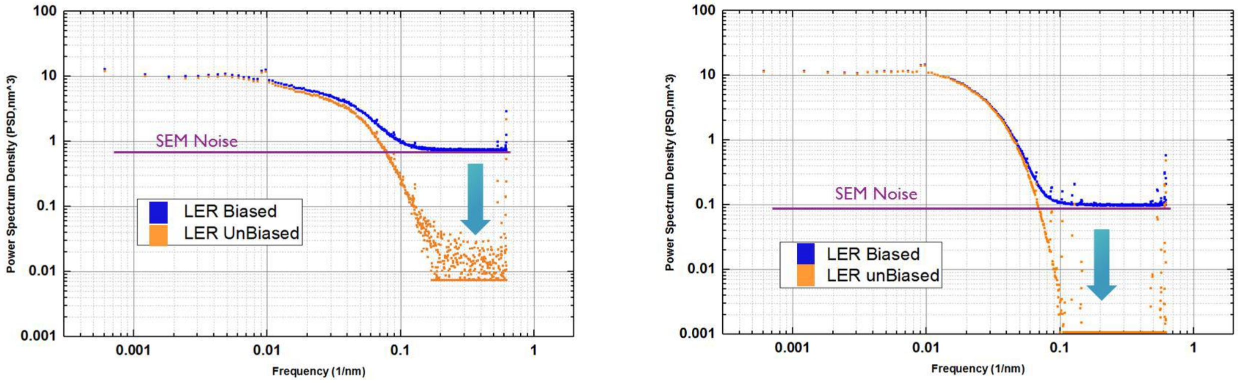

Figure 2: Flat floor level of SEM noise for images after lithography (a) and after etch (b) .

2.2 The effect of Pixel Size and Magnification

Other setting of crucial impact in the roughness measurement and in the PSD analysis are the pixel size and magnification used during the SEM images acquisition. The impact of these parameter on the shape of the PSD curve and on the flat floor level of the CD-SEM noise have been previously reported [2]. In general, as the pixel size is decreased, the high frequency plateau drops and the impact of the SEM noise becomes lower. Asymptotically the SEM noise is totally absent with a pixel size close to zero. By contrast, the impact of magnification on roughness is observed to be negligible if the pixel size is kept constant.

In this work, all the CD-SEM images used for the PSD analysis have been acquired using a standardized metrology setting, reported as imec Roughness Protocol [3].

3. PSD FOR MATERIAL CHARACTERIZATION

3.1 The influence of the stack

Line-space of chemically amplified resists (CAR) samples were coated on stacked wafers with different under-layers. This experiment was designed to understand how the roughness could be reduced with a proper underlayer selection. Four different material were used. Respectively from Stack 1 to 4, the resist was coated on 5nm organic underlayer, 5 nm spin-on-glass (SOG) type A, 10 nm SOG type B on 60nm amorphous carbon hard mask and 10nm of SOG type B on 65 nm spin-on-carbon(SOC).[4]

Top-down SEM images have been acquired on HITACHI CG-5000 scanning electron microscope. To avoid any possible tool to tool variability, all the measurements have been executed on the same tool. In figure 3,a sample image per stack .

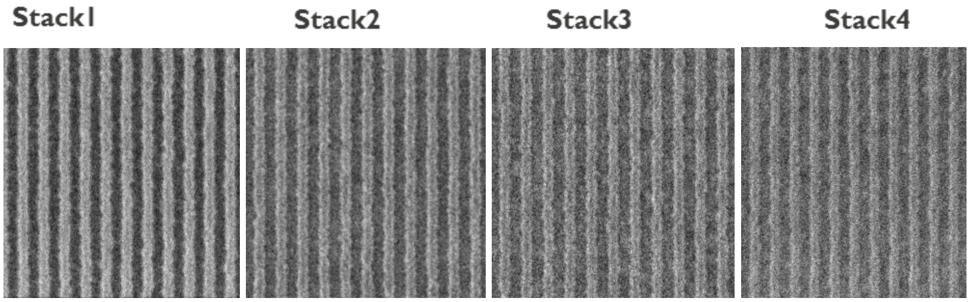

Figure 3: Top down CD-SEM images of 16 nm CD 32nm Pitch Lines-Spaces EUV CAR resist on different underlayers.

At first look, it is already possible to distinguish a difference in the image contrast from stack to stack. The PSD analysis was performed through Fractilia MetroLER TM commercial software. LWR results in Figure 4

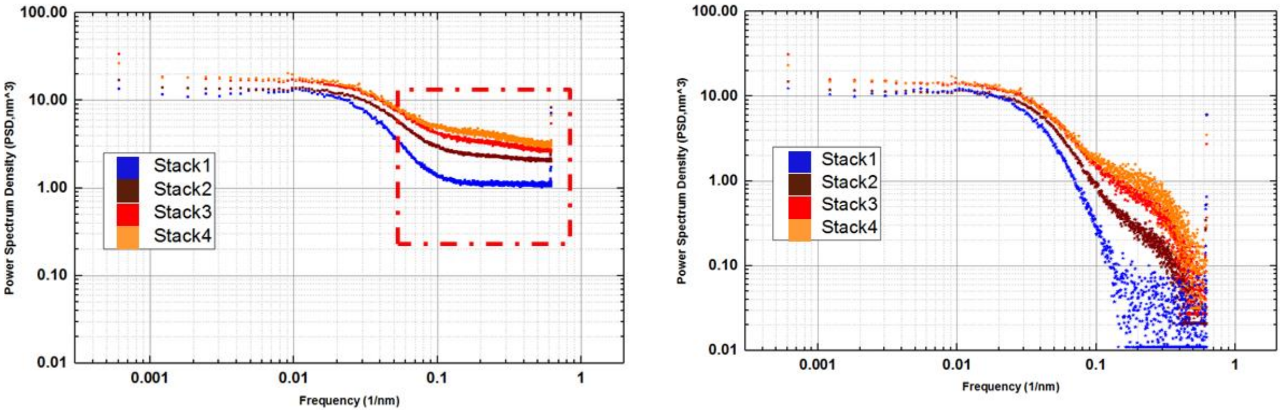

Figure 4: Biased LWR (left) vs Unbiased LWR (right) PSD for EUV CAR resist on different underlayers.

The PSD biased graph shows in the high frequency region, a clear difference of flat floor level of the CD-SEM noise. This difference is closely linked to the difference in the image contrast present in each sample due to the different charging effect of the SEM.

Consequently each sample has a different level of gray scale and the stack which has an organic film as underlayer, results to be the more contrasted and indeed the one with a lower level of CD-SEM noise. Obviously, since the area under a PSD-frequency graph is equal to the mean square value of the signal, then the root mean square(rms) which defines the LER/LWR values, will be effected by this uncorrected variance of the noise level.

Unbiasing the PSDs , in other words, the removal of the sample noise dependency, results to be the only way to be able to distinguish a true roughness improvement due to a certain underlayer.

Next we have studied the variance of the roughness with a three parameters model. As presented [5] , the exact relationship between variance and the other three PSD parameters depends on the exact shape of the PSD curve in the mid-frequency region, but can be approximate with :

$$\sigma_{LER}{}^{2} \approx \frac{PSD_{LER}(0)}{(2H+1)\,\xi_{LER}} \qquad (1)$$

where the term PSD(0), as explained in the introduction chapter, describe the low-frequency region of the PSD, H is the Hurst or roughness exponent and ξ is the correlation length.

In the figure 5, the trend of PSD (0) and Correlation Length is reported for each single stack. A gradual increase of the low frequency component can be observed moving from stack one to four, while the correlation length doesn't show any significant variation around a mean value. This is an indication that this parameter is barely affected by the choice of the underlayer but confirms to be tightly related to the resist.

Consequently to what shown in the figure 5 and from what also observed in figure 4, the organic underlayer seems to be the best choice aiming a low roughness lithography process.

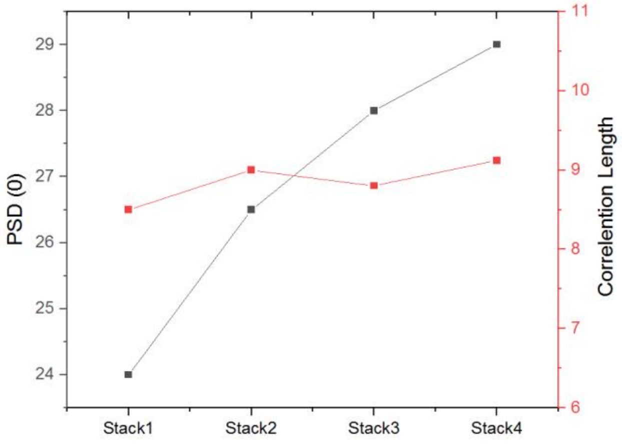

Figure 5: Plot of PSD (0) and Correlation Length values for each stack.

Another evidence of the close relation between correlation length and resist property is reported in the figure 6. Here a plot of the autocorrelation function for four different EUV resist is presented. Clearly there is a group of CAR resists, which show a correlation length around 9.6nm and a metal containing resist (MCR) with a correlation length of 6.1 nm.

The difference in the correlation length of the different type of resists is due to the difference in the resist Blur existing between them. Usually the MCR has a lower range or volume in which a photon is absorbed through the resist.

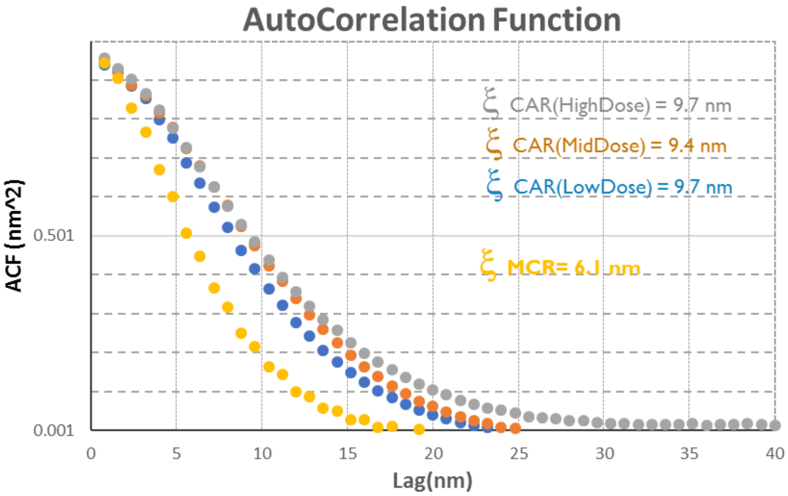

Figure 6: Autocorrelation plot for different EUV resists

4. PSD FOR PROCESS CHARACTERIZATION

Similarly to what presented in the previous chapter, the PSD analysis has been used to evaluate the impact of an etch smoothening treatment on the EUV resist lines.

As described in [6] and [7], a new technique utilizing a direct current superimposed (DCS) capacitively-coupled plasma (CCP) was used to enhance the etch selectivity to EUV resist with decreasing line width roughness (LWR).

This technique includes chemical and e-beam curing effects. The chemical structure of the photoresist is reformed, hardening its surface.

In this paper we report the LER results achieved using one of the stack presented in the previous chapter on which four different DCS condition were applied. In Figure 7 , the CD-SEM top-down images are presented.

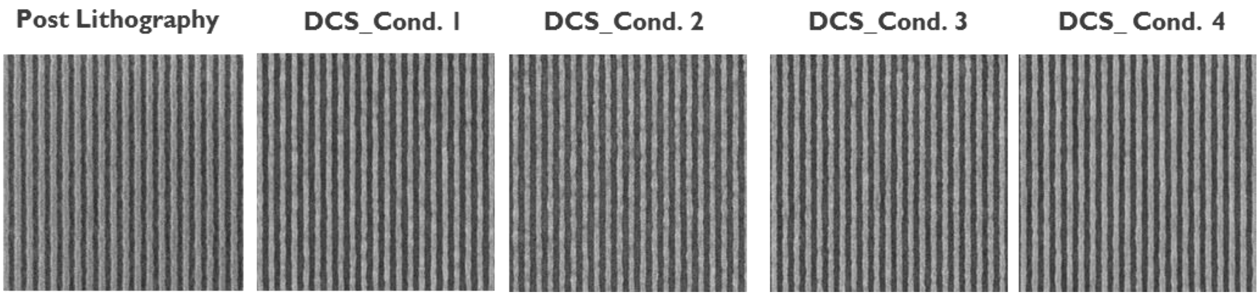

Figure 7:Top-down CD-SEM images of line-spaces after EUV exposure and with different DCS conditions applied

The images have been analyzed using Fractilia MetroLER TM commercial software. The results are reported in figure 8, 9 and 10.

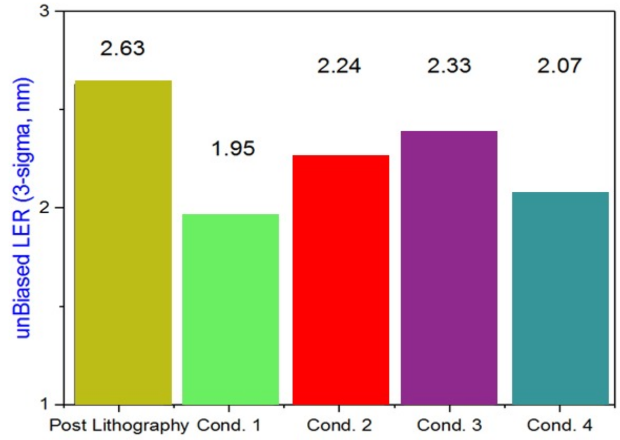

Figure 8: Unbiased LER Post Lithography and for the four different DCS conditions applied

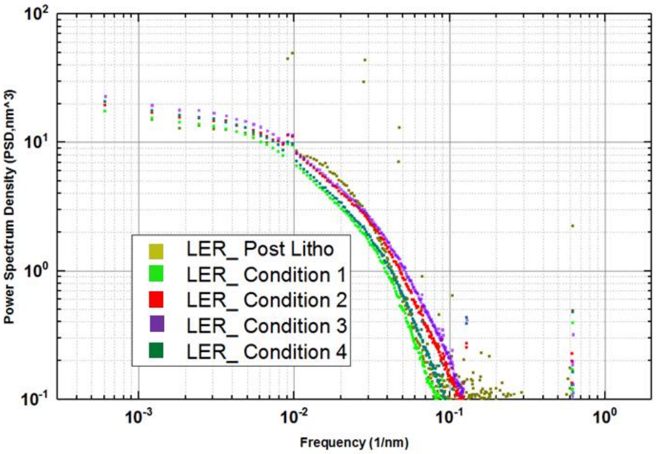

Figure 9: PSD LER curves of the DCS conditions applied to EUV lines-spaces

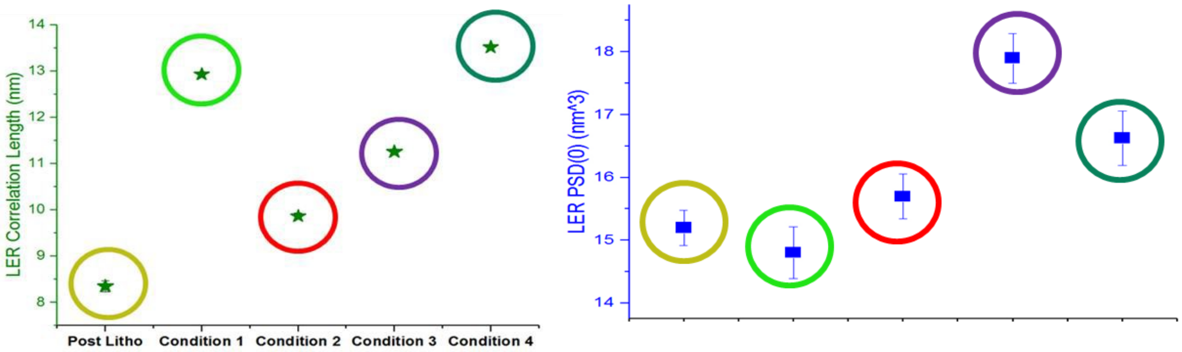

Figure 10 :LER Correlation Length (left) and PSD (0) (right)

From Figure 8, it's obvious that all the four conditions used separately on four different samples have successfully reduced the edge roughness compared to the post lithography result. More important at this point, result to be the understanding behind this different improvement achieved with the different conditions.

For this scope the use of the PSD analysis is then essential. Using again the 3 parameters model presented in the previous chapter, the understanding of the PSD curves become easier.

As reported by the values of the PSD (0), the low-frequency roughness is kept as the same level as post lithography. This is reflected in a quasi-perfect overlap of the two PSD curves in this range (figure 9). The other three conditions were not able to preserve the low long-range roughness. Clearly, the other curves show a higher trend in this region compared to the post lithography.

On the other hands, all the four conditions show an increase of the correlation length. This increase has an impact on the mid/ high-frequency range. Here indeed all the four curves of the DCS conditions show a lower trend. In other words, the etch smoothening plays a big role in the reduction of the high-frequency roughness. The best result is achieved indeed for the condition 1, as reported by the unbiased LER value, where the increase of the correlation length/ reduction of high-frequency roughness was obtained without damaging the low-frequency roughness. Moreover, a low PSD(0) is a stronger assumption compared to the possible increase of the correlation length. This is evident in the condition 4.

5. CONCLUSION

In this paper, we aimed to present at first, the necessity to use the PSD analysis as a powerful tool for the roughness characterization and understanding. In this optic, the effect of the SEM noise on the curves are not negligible and must be corrected through the unbiasing method.

The lithography results presented proved that lithography can control and minimize the low-frequency roughness, for instance with a proper selection of a certain underlayer. Also, we observed that a low correlation length at this stage could be beneficial for printability and resolution purposes. In addition, this value is closely linked to the resist blur.

The etch smoothening showed the best results when the PSD (0) was preserved as it comes from lithography. The roughness reduction is evident in the high-frequency regime obtained increasing the correlation length.

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