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Mathematical model for calculating speckle contrast through focus

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ABSTRACT

The significantly reduced wavelength and the reflective nature of EUV masks causes phase variations resulting from roughness on the mask to result in intensity variations when the wafer is out of focus. These variations should be understood and modeled to control LER and device yield. A typical approach to modeling the effects of roughness is to image many masks using a thin mask simulator. These images can then be statistically analyzed to get the speckle properties. A model already exists that can relate speckle contrast to LER.

This paper presents a method to compute the speckle image intensity using a single convolution with the roughness. This can be used to compute speckle through focus quickly. The presented technique takes into account defocus and the illumination coherence. It can be applied to phase roughness and amplitude roughness (reflectivity variations). In addition to speed improvements, the convolution kernel provides insights into the interaction of the source mask and mask roughness showing that, depending on the illumination coherence and defocus, not all roughness frequencies are attenuated equally.

Keywords: extreme ultraviolet, lithography, mask roughness, speckle, thin mask, phase roughness

1. INTRODUCTION

In extreme-ultraviolet lithography the shift to a 13.5nm wavelength has resulted in the use of reflective masks and optics. This transition brings with it a new problem in lithography where the roughness of the mask and optics can significantly degrade the image performance by adding intensity variations at the wafer when there is defocus. When light hits the mask the light reflecting from the top of hills will travel a shorter distance than the light reflecting from the bottom of hills. This results in a phase difference proportional to twice the roughness. Additionally, the small wavelength means that roughness that would not have been significant at 193nm is now a significant phase effect. The phase variations will cause the intensity to vary when the wafer is not at focus.

Previous mathematical analysis of how mask roughness was provided by Beaurdry and Milster[1,2]. The effect of roughness on image formation in EUV systems has been examined[3] and was found to have an impact on line edge roughness[4,5]. Other experimental work[6] has found that the effect of mask roughness only significantly impacts LER above 500pm.

The standard method for examining the effect of roughness is to image a sample of roughness using a thin mask simulator. This simulator performs a convolution of the electric field at the mask with the point spread function of the imaging system, which considers defocus, to compute the electric field at the wafer. The field is then squared to get the intensity. Lastly, if the illumination is partially coherent this computation must be done for all source points since they are mutually incoherent. Taking the intensity is a non-linear operation so it is difficult to optimize. The method described in this paper is able to simplify this computation for small roughness by forcing the step of taking the intensity to be linear. The result is a formula that is able to compute speckle using a single convolution with the mask roughness.

2. MODEL DERIVATION

2.1 Derivation

Consider the electric field at the mask where the small height variations, H, in the mirror cause small phase variations and there are small reflectivity variations, A.

$$E_{mask} = \big(1 - A(x,y)\big)e^{\frac{4\pi i H(x,y)}{\lambda}} = 1 + \bar{E}_{mask} \qquad (|\bar{E}_{mask}| \ll 1) \tag{1}$$

If we now consider the pupil function $P(\vec{f})$ and a set of illumination angles corresponding to a source mask indicated by $\vec{L}$ in the pupil we can write the electric field at the wafer as

$$E_{wafer} = \mathrm{F}^{-1}\{\, \mathrm{F}\,\{E_{mask}\}\, P(\vec{L} + \vec{f})\,\} \tag{2}$$

For wavelength $\lambda = 13.5nm$. If the wafer is a distance d out of focus $P(\vec{f})$ would be

$$P(\vec{f}) = \begin{cases} e^{i\,\pi\,d\,\lambda\,|\vec{f}|^2} & |\lambda\vec{f}| < NA \\ 0 & |\lambda\vec{f}| > NA \end{cases} \tag{3}$$

When we integrate over all the angles that the mask is being illuminated from (ie the entire source mask) we get

$$I = \iint E_{wafer}\, E^*_{wafer}\, d\vec{L} \tag{4}$$

$$I = \iint \big(F^{-1}\{\, F\,\{E_{mask}\}\, P(\vec{L} + \vec{f})\,\}\big)\,\big(F^{-1}\{\, F\,\{E^*_{mask}\}\, P^*(\vec{L} - \vec{f})\,\}\big)\, d\vec{L} \tag{5}$$

Substituting in the expression for E_{mask} and expanding

$$I = \iint \begin{bmatrix} F^{-1}\{\, F\{1\}P(\vec{L}+\vec{f})\,\}\, F^{-1}\{\, F\{1\}P^*(\vec{L}-\vec{f})\,\} \\ +\, F^{-1}\{\, F\{\bar{E}_{mask}\}P(\vec{L}+\vec{f})\,\}\, F^{-1}\{\, F\{1\}P^*(\vec{L}-\vec{f})\,\} \\ +\, F^{-1}\{\, F\{1\}P(\vec{L}+\vec{f})\,\}\, F^{-1}\{\, F\{\bar{E}^*_{mask}\}P^*(\vec{L}-\vec{f})\,\} \\ +\, F^{-1}\{\, F\{\bar{E}_{mask}\}P(\vec{L}+\vec{f})\,\}\, F^{-1}\{\, F\{\bar{E}^*_{mask}\}P^*(\vec{L}-\vec{f})\,\} \end{bmatrix} d\vec{L} \tag{6}$$

Since $\bar{E}_{mask}$ is very small and the last term is goes as $|\bar{E}_{mask}|^2$ the last term can be ignored because it is much smaller than the other terms. With some reordering of operators this simplifies to

$$I = \iint |P(\vec{L})|\, d\vec{L} + F^{-1}\left\{K_{re}(\vec{f}) \cdot F\{Re\{\bar{E}_{mask}\}\}\right\} + F^{-1}\left\{K_{im}(\vec{f}) \cdot F\{Im\{\bar{E}_{mask}\}\}\right\} \tag{7}$$

where $\iint |P(\vec{L})|\, d\vec{L} = 1$ as long as $|\lambda\vec{L}| < NA$ which is generally the case in practice and

$$K_{re}(\vec{f}) = \iint P(\vec{L})P^*(\vec{L}-\vec{f}) + P^*(\vec{L})P(\vec{L}+\vec{f})\, d\vec{L} \tag{8}$$

$$K_{im}(\vec{f}) = i \iint P(\vec{L})P^*(\vec{L}-\vec{f}) - P^*(\vec{L})P(\vec{L}+\vec{f})\, d\vec{L} \tag{9}$$

In equation (1) we can Taylor expand the exponential and take the first real and imaginary term to get

$$Re\{\bar{E}_{mask}\} \approx A(x,y) \tag{10}$$

$$Im\{\bar{E}_{mask}\} \approx \frac{1}{2}\,\frac{4\pi H(x,y)}{\lambda} \tag{11}$$

This result shows that under the approximation that $(|\bar{E}_{mask}| \ll 1)$ the speckle intensity can be given by a single convolution of the amplitude roughness or the phase roughness with the convolution kernels given by $K_{re}(\vec{f})$ and $K_{im}(\vec{f})$, respectively.

2.2 Computing Contrast

In some cases it is enough simply to know the overall contrast of the speckle. Contrast is given by

$$Contrast = \frac{\sqrt{\overline{I^2}}}{\bar{I}} \tag{12}$$

$\sqrt{\bar{I}^2}$ is the root mean square of the intensity and $\bar{I}$ is the mean intensity. In this case it is possible to apply Parseval's Theorem to compute the contrast directly from the power spectrum of the roughness and functions K_{re} and K_{im}.

$$Contrast^2 = \iint \left| K_{re}(\vec{f}) \cdot F\{Re\{\bar{E}_{mask}\}\} + K_{im}(\vec{f}) \cdot F\{Im\{\bar{E}_{mask}\}\} \right|^2 d\vec{f} \qquad (13)$$

If only phase or amplitude roughness is considered or if the amplitude and phase roughness are entirely uncorrelated then the cross term of the square will cancel leaving just

$$Contrast^2 = \iint \left| K_{re}(\vec{f}) \right|^2 \cdot PSD_A(\vec{f})\, d\vec{f} + \iint \left| K_{im}(\vec{f}) \right|^2 \cdot PSD_H(\vec{f}) \cdot \left(\frac{2\pi}{\lambda}\right)^2 d\vec{f} \qquad (14)$$

PSD is the power spectral density which says how much of a particular frequency is present. A consequence of this is that it is no longer necessary to work with specific mask roughness images because the power spectrum of the mask is enough to characterize the spectrum of the speckle.

2.3 Limitations

Intensity needs to be real. Equation (7) might produce an intensity that is complex. The condition for intensity to have no imaginary component is that the convolution kernels from equation (8) and equation (9) are symmetric. This constraint along with the assumption made in Equation (1) gives three constraints on this method.

1. ($|\bar{E}_{mask}| \ll 1$) so that the cross term in the intensity can be ignored
2. The convolution kernels must be symmetric so that intensity is real

In practice it is possible that even when these conditions are fulfilled the intensity calculated will have a small imaginary component. This component should be ignored since it is a result of numerical errors. It should also be remembered that this derivations applies only for a clear field. If the mask is patterned with lines or other features then there will be diffraction and the method will no longer apply exactly.

3. MODEL ANALYSIS

3.1 Accuracy

To test the accuracy of the method several mask roughness images were used that match AFM measurements of the surface of EUV masks. The roughness of these was approximately 100pm and the masks were 512px by 512px. These were then imaged using a thin mask simulator and using equation (7). NA = 0.3, λ = 13.5nm.

When the roughness of the mask was varied the difference between the actual image (as computed by the thin mask simulator) and the model diverges approximately quadratically as shown in Figure 1.

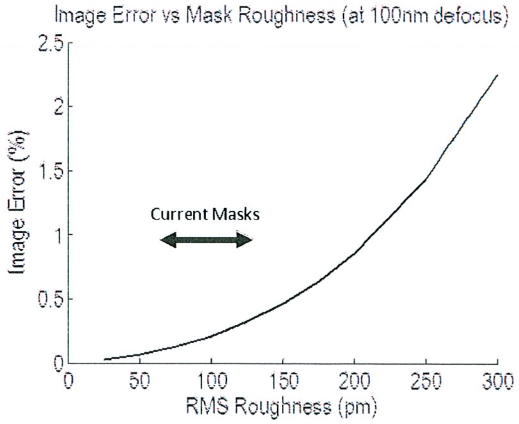

Figure 1. This is the standard deviation of the error of all the points in the correct image minus the points in the image calculated with equation (7). The arrow indicates the range of actual masks. The error is quite low in that range.

When the contrast is computed for those masks and compared to the contrast of simulator images the match is very good as shown in Figure 2.

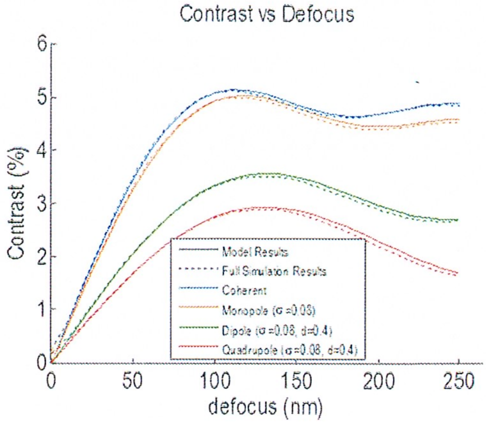

Figure 2. The dashed lines are the contrast computed by the thin mask simulator and the solid lines are computed with Equation (7). The actual contrast values may not be representative of actual masks because AFM roughness is not necessarily phase roughness since it is only measuring the top surface.

3.2 Speed

The typical method of computing the speckle would image the mask for each source point and then sum up the final intensities. The presented method takes everything into account in a single convolution. There is therefore an asymptotic (big O) improvement. The performance of this method is

$$\mathbf{S} \times \mathbf{D} \times \mathbf{F} \; + \; \mathbf{D} \times \mathbf{F} \times \log(\mathbf{F}) \tag{15}$$

S is the number of source points, **D** is the number of defocus values computed, and **F** is the number of frequencies or the size of the mask being computed. The first term is the complexity of computing the convolution kernel and the second term is taking the convolution. Without this method the performance would be

$$\mathbf{S} \times \mathbf{D} \times \mathbf{F} \times \log(\mathbf{F}) \tag{16}$$

This shows that for large numbers of source points the performance of the single convolution is better, otherwise it is similar. If only the contrast is needed then using the method explained in Section 2.2 it is possible to skip a Fourier Transform and the method improves to

$$\mathbf{S} \times \mathbf{D} \times \mathbf{F} \; + \; \mathbf{F} \times \log(\mathbf{F}) \tag{17}$$

This says that when considering a large mask (giving a large **F**), it is cheaper by a factor of log(**F**) to compute contrast for more focus points. Traditionally this trick could not be applied because contrast must be computed on intensity, not field, which results in a non-linear operation.

4. SPECKLE SPECTRUM

Since speckle can be computed using a single convolution it is possible to look at the convolution kernel to see how frequencies on the mask transfer to speckle intensity.

An insight gained from the convolution kernel is that not all frequencies in the mask are transferred to speckle. In particular certain frequencies are amplified. Low frequency phase roughness tends to get blocked out whereas high frequency amplitude roughness is blocked out. Figure 3 shows what the convolution kernels look like for three different illuminations. The most notable behavior to note is that there are peaks at particular frequencies.

The behavior of the convolution kernel with varying focus depends on the illumination. For a monopole illumination the dependence is approximately sinusoidal and with increasing defocus the frequency that is least attenuated by the kernel decreases resulting in lower frequency speckle with increasing defocus. This can be seen in Figure 4. This behavior is not present in all illuminations, however. For quadrupole illumination the effect of roughness increases with defocus, but the frequencies being attenuated do not move as much. This can be seen in Figure 5. As a result the speckle frequency content of quadrupole illumination will not depend on defocus as much as with monopole illumination.

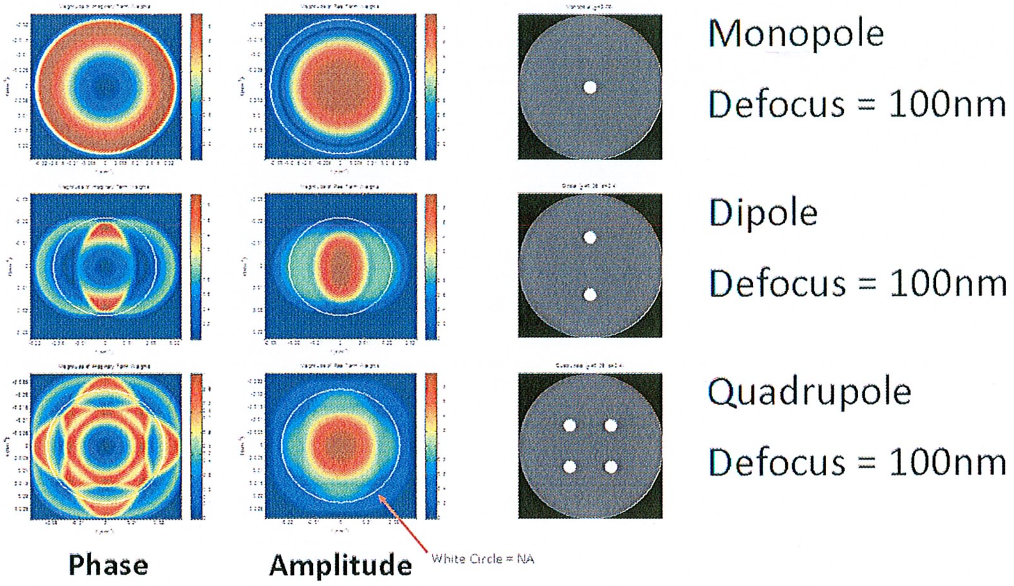

Figure 3. The plots show the shape of the convolution kernel K_{re} and K_{im} for phase and amplitude roughness for different illuminations. The white circle shows the NA of the system.

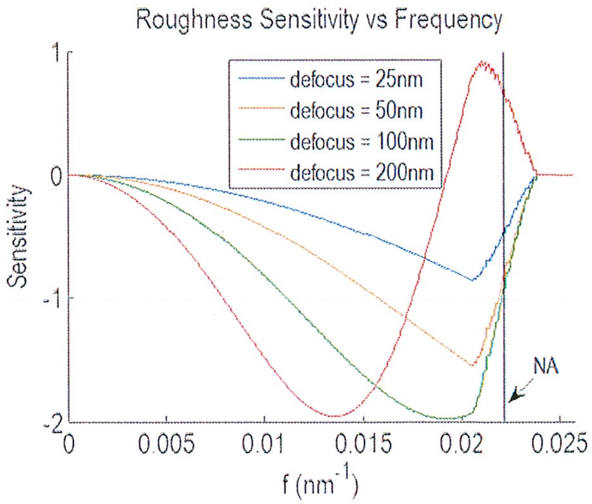

Figure 4. This is a horizontal slice ($f_x = 0$, $f_y > 0$) from the monopole phase roughness convolution kernel. The vertical line is the NA of the system. This shows that for monopole illumination the peak frequency in the speckle changes with defocus.

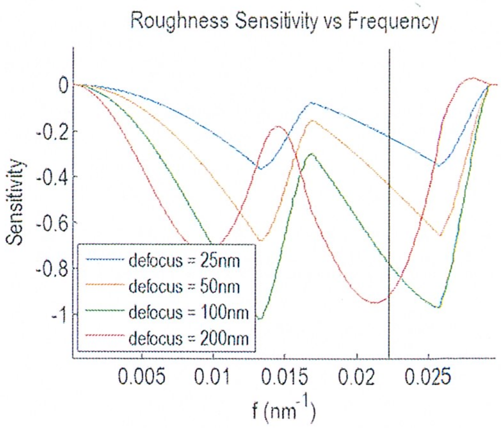

Figure 5. This is a horizontal slice ($f_x = 0$, $f_y > 0$) from the quadrupole phase roughness convolution kernel. The vertical line indicates the NA. This shows that for quadrupole illumination the peak frequencies do not change significantly with defocus.

5. MODEL APPLICATIONS

This method can be used to more quickly simulate the effect of mask roughness on imaging and in particular to understand how the roughness affects the images. In particular contrast can be used to estimate LER.

An empirical model by B. M. McClinton is able to estimate LER directly[1] from the clear field speckle contrast using:

$$LER = 3 \cdot S \frac{1}{I \cdot ILS}$$

S is the contrast. I is the threshold intensity, and ILS is the image log slope. Contrast can be easily and quickly calculated using the described method making it possible to quickly estimate the effect of roughness and illumination on LER.

The ability to use a single convolution to compute speckle can also be used to easily extract the effective phase and amplitude roughness from speckle images taken using a 13.5nm microscope. Ordinarily a phase retrieval technique would be needed to extract the roughness, but these techniques do not generally work as well for partially coherent illumination and a combination of phase and amplitude roughness. With this method extracting roughness becomes a single deconvolution for phase roughness only and a straight forward series of deconvolutions to get both amplitude and phase.

6. CONCLUSION

We have developed a method that is able to easily compute the speckle image directly from the effective phase and amplitude roughness of a mask using a single convolution. The kernel of the convolution makes it apparent which frequencies in the roughness result in the speckle and as a result can predict the statistical properties of the speckle image directly without the need for an ensemble of mask images. The ability to see speckle frequencies directly can be useful in evaluating the interaction of a particular source mask with mask roughness and calculating the impact on LER. The model could also be used to extract the effective phase roughness when only the intensity of speckle is measurable.

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REFERENCES

[1] Beaudry, N. A., Milster, T. D., "Imaging properties of a patterned rough surface: effects of roughness correlation and partial coherence," Optical Engineering 44(7), 078001 (2005).

[2] Beaudry, N. A., Milster, T. D., "Effects of object roughness on partially coherent image formation," Optics Letters 25(7), 454 (2000).

[3] Beaudry, N. A. and Milster, T. D. "Effects of mask roughness and condenser scattering in EUVL systems,"Microlithograpy 99, 653-662 (1999).

[4] George, S A., Naulleau, P. P., Gullikson, E. M., Mochi, I., Salmassi, F., Goldberg, K. A., and Anderson, E. H., "Replicated mask surface roughness effects on EUV lithographic patterning and line edge roughness," SPIE Advanced Lithography, 79690E (2011).

[5] McClinton, B. M., and Naulleau, P. P., "Mask-roughness-induced line-edge roughness: rule of thumb," J. Micro/Nanolith. MEMS MOEMS. 9(4), 041208 (2010).

[6] Pret, A. V., Gronheid, R., Younkin, T. R., Leeson, M. J., Yan, P., "Impact of EUV Mask Surface Roughness on LER," Proc. SPIE 8322, 83220N (2012).

DISCLAIMER

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