Recovering Effective Amplitude and Phase Roughness of EUV Masks

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ABSTRACT

Roughness in EUV masks can be induced at the substrate or during the deposition process in the multilayer, and this roughness causes speckle when the mask is used for imaging. The 13.5-nm wavelength light penetrates into the multilayer and interacts mostly with the roughness that is replicated through the multilayer. AFM measurements of the substrate or surface cannot fully capture the effect of the roughness on imaging.

We present a method to extract the phase and amplitude roughness from measurements taken using an actinic microscope. The method is non-iterative and is able to properly consider partial coherence, aberrations, and image noise. It works by applying the small phase approximation to linearize the step of taking the intensity from electric field. We also analyze the sensitivity of the method to various miscalibrations that might occur when applying it to measured data.

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

1. INTRODUCTION

EUV lithography requires the use of reflective masks. These masks are made using multilayers that have Bragg reflection at 6 degrees. Roughness on the substrate of the multilayer or roughness introduced during the multilayer deposition process can result in phase roughness in the reflected light. The electric field leaving the mask will be scattered by any roughness that is replicated in the multilayer. This can be modeled as a phase variation in the uniform wavefront that is expected to leave the mask. When the mask is imaged, this roughness causes intensity variations—speckle—that vary with focus.[1,2] These variations can cause LER in patterns and degrade the performance of the tool.[3]

To date, this roughness has been measured primarily with AFM at the substrate or at the top of the multilayer. Yet, these measurements do not probe the depth of the multilayer in the same way that the EUV light does.[4]Scatterometry measurements have shown that the AFM measurements do not accurately match the roughness perceived by the EUV light.[5]AFM and scatterometry don't measure the amplitude roughness (variations in the reflectivity) that could accompany the phase roughness.

We present an alternative method to measure the effective roughness in the multilayer using an actinic microscope. Taking advantage of the roughness being small, we are able to extract phase roughness as well as amplitude roughness. Moreover, this method is able to consider partial coherence and weak aberrations.

2. PHASE RECOVERY METHOD

2.1 Mathematical Assumptions

The mathematics of the proposed method rely on the weak phase approximation and the thin mask approximation—considering only scalar fields. The detailed derivation is provided in a previous paper.[6] The assumption demands that the electric field at the image plane can be decomposed into a DC field plus a small perturbation.

$$E_{img} = 1 + \tilde{E} \qquad \left(|\tilde{E}| \ll 1\right) \tag{1}$$

$$I = \left|E_{img}\right|^2 = 1 + 2Re\{\tilde{E}\} + \left|\tilde{E}\right|^2 \tag{2}$$

The quadratic term in Equation [2] is dropped, making intensity linear in $\tilde{E}$, and the real term can be expanded so that the intensity can be written as a sum of two convolutions.

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$$I = 1 + Re\{E_{obj}\} * K_{re} + Im\{E_{obj}\} * K_{im} \tag{3}$$

Where $*$ means convolution, E_{obj} is theelectric field perturbation of the mask, andK_{re}, K_{im} are the transfer functions that capture the effects of roughness on speckle.

$$K_{re} = F^{-1}\left\{\sum_{L=source} P(L)P^*(L-f) + P^*(L)P(L+f)\right\} \tag{4}$$

$$K_{im} = iF^{-1}\left\{\sum_{L=source} P(L)P^*(L-f) - P^*(L)P(L+f)\right\} \tag{5}$$

$L$is a source point in the illumination, $f$is a frequency, $P(f)$ is the pupil function, and X^*means the complex conjugate of X.

Using the equations for K_{re} and K_{im} it is possible to calculate a transfer function that describes the coupling between individual amplitude and phase frequencies and image plane speckle.

2.2 Fitting the Data

Taking the equations above, it is possible to invert equation (3) in the Fourier domain. For each frequency we can set up a matrix equation:

$$\begin{bmatrix} \cdots \\ F\{I-1\}_f \\ \cdots \end{bmatrix} = \begin{bmatrix} \cdots & \cdots \\ F\{K_{re}\}_f & F\{K_{im}\}_f \\ \cdots & \cdots \end{bmatrix} \begin{bmatrix} F\left\{Re\{E_{obj}\}\right\}_f \\ F\left\{Im\{E_{obj}\}\right\}_f \end{bmatrix} \tag{6}$$

Each row on the left corresponds to a measurement. The process of recovering the object is done by solving this system using least squares.For some frequencies, such as those outside the pupil, this matrix will be singular or nearly singular. These frequencies will not be reconstructed reliably and need to be explicitly ignored.

3. ACCURACY AND ERRORS

To study the accuracy of this method, we simulated a random mask with 50 pm (0.0075λ) rms phase roughness and 1% rms amplitude roughness. The roughness PSD was uniform up to 1.5 of the NA frequency and zero elsewhere. We then used a 2D thin mask simulator to generate a series of through focus images under various illumination conditions and aberrations. For the noise analysis we added Gaussian noise with a standard deviation of5%. The wavelength used in the simulator was 13.5 nm, the NA was 0.33 and the illumination used was 0.1 sigma.

To characterize the errors we chose:

- **Amplitude Error** = (recovered amplitude – true amplitude) / rms of true amplitude
- **Phase Error** = (recovered phase – true phase) / rms of true phase
- **Reconstruction Error** = (expected speckle given recovered amplitude and phase – actual measured speckle) / contrast in actual measurement

The amplitude and phase error are the errors relative to the actual mask. They correspond to "the recovered amplitude/phase is off by X% of the real amplitude/phase." The reconstruction error is an error metric that could be calculated from actual measurements where the true roughness is not known. It corresponds to how well the recovered field predicts the measurement or "the expected speckle is off by X% of the measured speckle."

3.1 Effect of Amplitude and Phase Size

The method relies on the phase and amplitude being small. We examined the effect of larger or smaller phase or amplitude roughness on the accuracy of the method. Figure 1 shows the effect of increasing amplitude roughness. Figure 2 shows the effect of increasing phase roughness. Both figures additionally show the effect of ignoring the presence of amplitude roughness to illustrate that methods not considering amplitude roughness, such as scatterometry assuming a phase roughness, can fail to fully describe the mask.

The amplitude error increases with phase roughness because the quadratic term that we ignore produces speckle frequencies near the edge of the pupil that behave like amplitude roughness and are at frequencies where amplitude induced speckle is expected to be weakest.

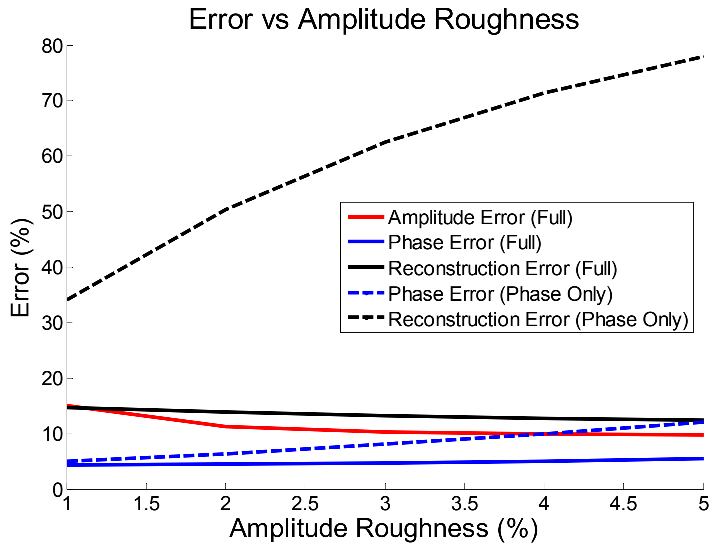

Figure 1.For this plot the phase roughness was kept constant at 50pm rms. For small amplitude roughness the phase reconstructed without considering amplitude roughness is almost equally accurate. For larger amplitude roughness it becomes more important to consider the both types of roughness. Since the amount of amplitude roughness is not known, it is better to consider both.

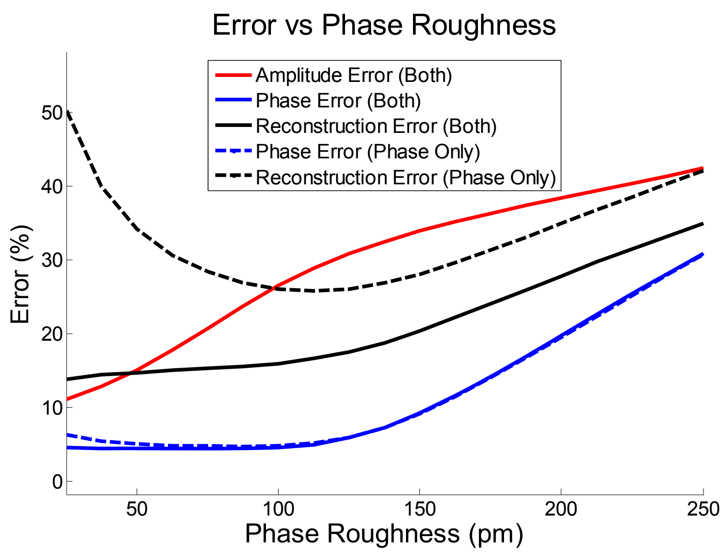

Figure 2.For this plot the amplitude roughness was kept constant at 1%. The increase in amplitude error is due to the effect of the quadratic term in Equation [2].

3.2 Incorrect Focus

The pupil function depends on focus at each plane. It is likely that the exact focus position of each measurement is not known and it is necessary to guess what the focus at each plane is. Typically a microscope will take a focus series with constant steps so we will consider an error in the offset from the correct focus and an error in the step size. Figure 3 shows the error of the reconstruction when the offset is incorrect. This means every plane has a focus that is wrong in the same direction by X nm.We find that phase is not very sensitive to this error whereas theamplitude is sensitive because those frequencies are coupled into speckle most strongly near focus. Figure 4 shows how the error varies with a step-size error in the stage motion, calculated with the correct focal offset. This error has the odd property that the minimum in the reconstruction error is not guaranteed to be at the true value of the parameter. This is an artifact of filtering the frequencies considered in the metrics. This was not seen in any other parameters.

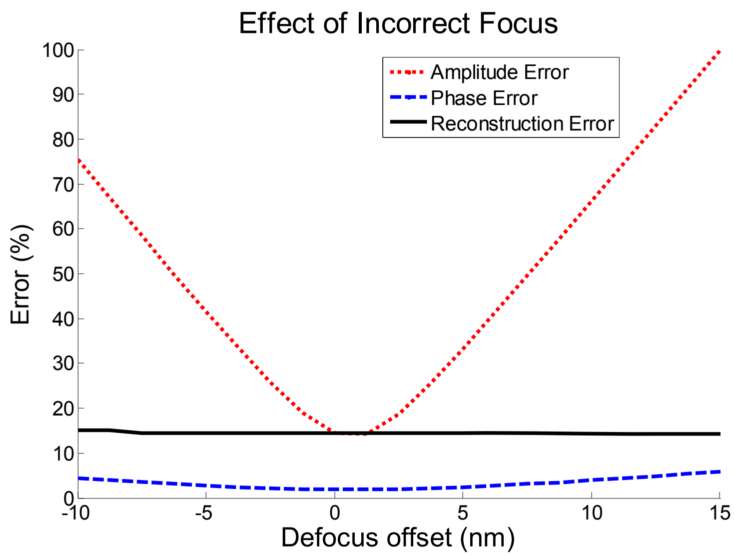

Figure 3.This plot shows how the errors change if the focus assumed for all the measurement planes was incorrect by x. The amplitude error is very sensitive because those frequencies are only strongly present near focus. The phase error is not as sensitive because those frequencies produce speckle mostly at large defocus. The reconstruction error is not very sensitive because some of the error in defocus position can be mixed into the amplitude and phase roughness – essentially propagating the roughness.

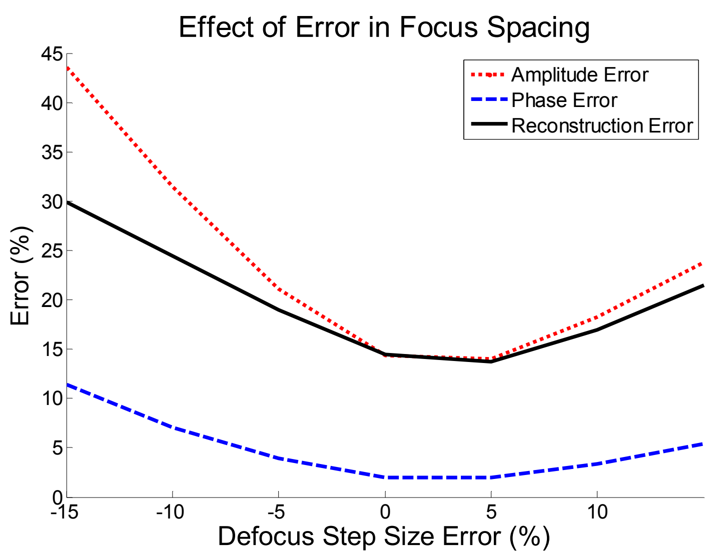

Figure 4.This plot shows how the errors are affected if the focus spacing is off by some percentage. The effect on the errors is not huge over small ranges, but there is an interesting effect. The reconstruction error is not minimized at the correct value. This suggests that it is not possible in all cases to find the correct measurement parameters by minimizing the reconstruction error.

3.3 Image Noise

In a microscope there will be detector noise and shot noise. For the analysis we assume that this noise has a Gaussian distribution and is added to the intensity images. We added 5% noise, which is comparable to the contrast giving an SNR close to 1.The recovered field does not match the measurements perfectly because the measurements contain noise. This can be seen in Figure 5 where the contrast curve of the predicted measurements does not line up with that of the measurement. This discrepancy is entirely due to the noise and when compared to the contrast curve that would have been measured without noise the difference disappears. Figure 6 shows the errors of the algorithm. The amplitude and phase error increased slightly due to the noise.The reconstruction error went up dramatically because in the way that error is calculated the noise adds directly to the error. As a result that increase in error does not reflect a poor performance of the algorithm butin fact handles noise very well because it relies on least squares.

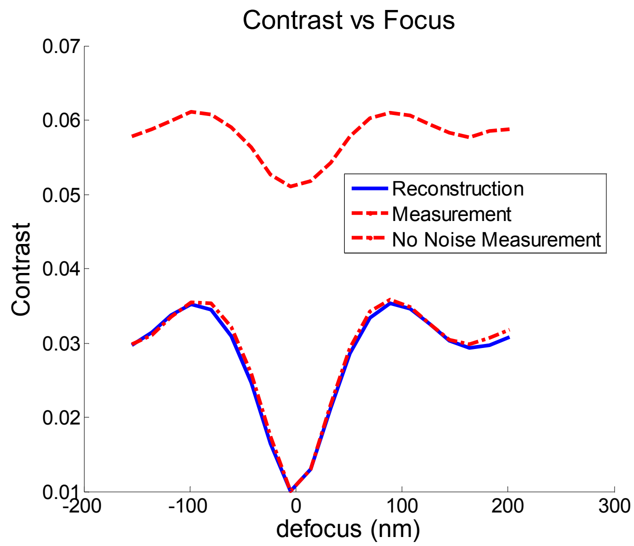

Figure 5. This plot shows the contrast through focus. The reconstruction doesn't match the measured contrast curve (solid red) because those measurements contain noise. It does match the contrast curve that would have been measured without noise (dashed red). The algorithm is able to remove the effect of Gaussian noise because it is based on least squares.

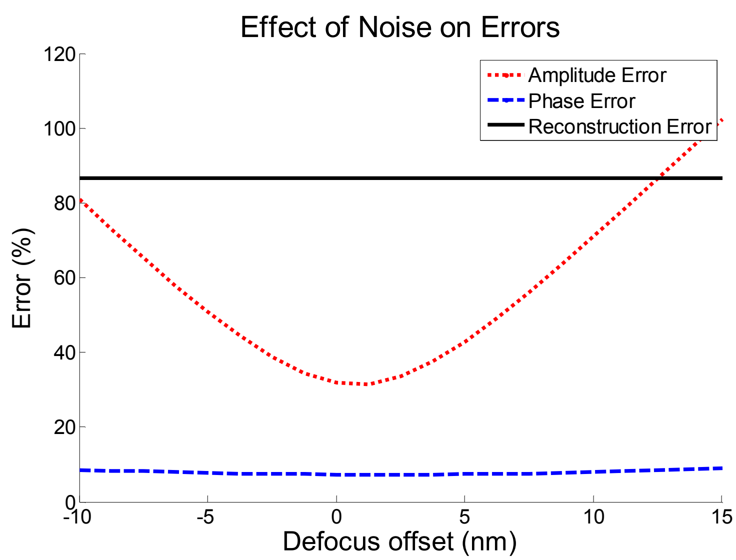

Figure 6. The amplitude error and phase error increased slightly. The reconstruction error increased because the measurement noise is not reconstructed, as intended, and so appears as an error between the reconstructed measurements and the actual measurements with noise. This increase in error is not a true error, though, it just appears as such because of the noise.

3.4 Incorrect Illumination

One of the advantages of the proposed algorithm is that it works in the presence of partial coherence. This introduces additional errors from uncertainty in the illumination. Figure 7 shows what the effect of assuming the wrong illumination is on the reconstruction. For this simulation the true illumination is 0.2 sigma. The reconstruction error is minimized with the correct illumination.This allows us to assume different illuminations and minimize the reconstruction error.

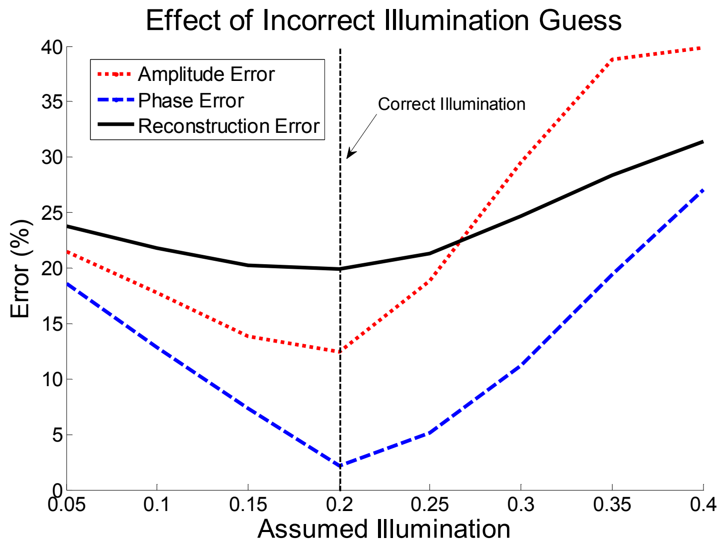

Figure 7. This plot shows how well the reconstruction works if the assumed partial coherence is incorrect. The correct illumination was 0.2 sigma, rather than 0.1 used for the other simulations. The phase error is most sensitive to this uncertainty, but the sensitivity of the reconstruction error suggests it is possible to minimize this effect. Note that the reconstruction error is larger than in the other analyses because the contrast (in the denominator of the metric) is lower for the less coherent illumination.

3.5 Aberrations

The microscope may also have aberrations affecting the images. If these aberrations are known they can be included in the pupil function, $P(f)$. The reconstruction error is not very sensitive to small aberrations, below 0.1 waves. This can be explained by the aberrations being combined with the mask to produce the image field that is being reconstructed.

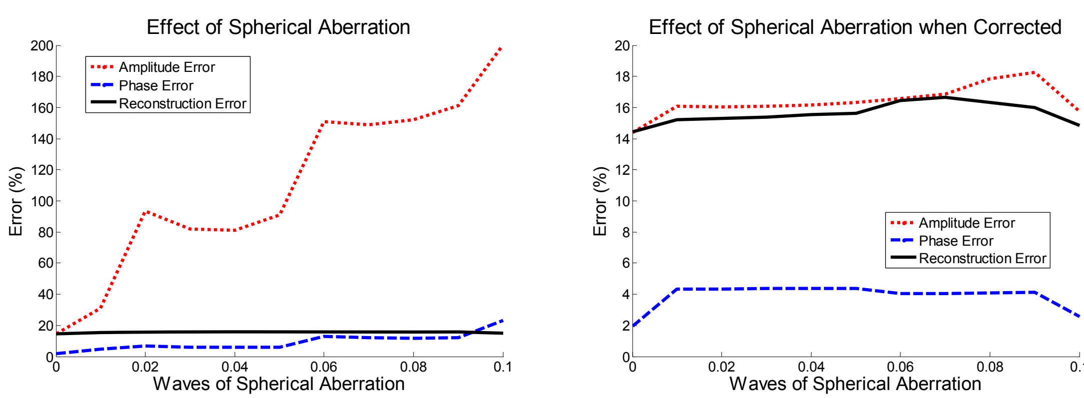

Figure 8. The plot on the left shows how the accuracy of the reconstruction degrades if spherical aberration is present. If the aberration is known, the aberration has a much smaller effect on the reconstruction.

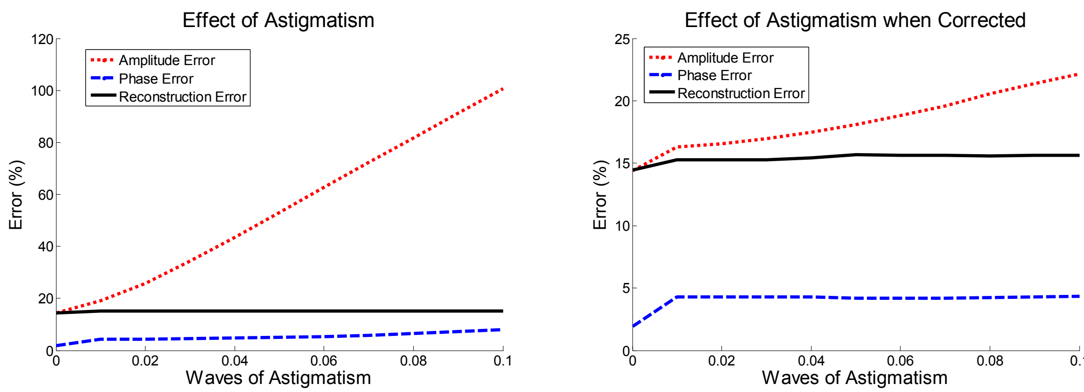

Figure 9.Uncorrected Astigmatism will also degrade the reconstruction. It has a smaller effect on the phase reconstruction than the amplitude.

4. CONCLUSION

We have outlined a method for recovering the phase and amplitude roughness of EUV masks using an actinic microscope. It is able to handle partial coherence and considers the impact of clipping at pupil due to the NA. The method takes advantage of the roughness being small relative to the overall reflectivity. The amplitude reconstruction is more sensitive to errors than the phase reconstruction. The recovery is sensitive to aberrations, but if they are known their impact on the reconstruction is mostly eliminated by including them in the pupil function. The algorithm is able to mostly remove the effect of noise because it combines multiple measurements. The method can be applied to measurements of EUV masks using an actinic microscope to recover the amplitude and phase roughness.

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