Resolution limit and photon flux dependency in EUV ptychography

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ABSTRACT

With the transition of EUV lithography to high-volume manufacturing, EUV mask metrology has become a critical requirement, and for future technology nodes, the challenges will increase. RESCAN, a lensless actinic microscope dedicated to EUV mask inspection under development, is based on coherent diffraction imaging (CDI) where the complex-amplitude image of the sample is obtained through its diffraction spectra measured with a pixel detector. While this approach can overcome the disadvantages and limitations of conventional optical imaging systems, in CDI, the quality of the recorded diffraction data is crucial for the reliable reconstruction of a high-resolution image. Ultimately, the signal-to-noise ratio of the recorded diffraction data depends on several parameters, such as the reflectance of the sample, the quantum efficiency of the detector, its full well capacity, and the intensity of the illumination. This paper investigates the optimal photon flux for RESCAN and analyzes the relation between the image quality and the EUV illumination intensity for a CDI-based imaging tool dedicated to EUV mask inspection and review.

Keywords: EUV mask, metrology, coherent diffraction imaging, ptychography, defect inspection

1. INTRODUCTION AND METHOD

Accurate imaging of the extreme ultraviolet (EUV) mask is essential in EUV lithography. At Paul Scherrer Institute (PSI), we are developing RESCAN (Reflection-mode EUV SCANning microscope), a ptychography-based microscope dedicated to actinic patterned mask inspection (APMI) [1-4]. It is a synchrotron-based platform installed at the XIL-II beamline of the Swiss Light Source (SLS). In the current version of the tool, the synchrotron beam, generated by an undulator, is spatially filtered with a pinhole, and its wavelength is controlled by a spherical grating monochromator which delivers a bandwidth ratio of $\lambda/\Delta\lambda=1500$ at 13.5 nm. The EUV beam is focused by a multilayer-coated concave mirror onto an EUV mask. The incidence angle, controlled by a flat folding mirror, is around 6° from the normal to the sample surface. The maximum collection numerical aperture (NA) determines the ultimate resolution limit of the setup and is defined as

$$NA = \sin\left(\tan^{-1}\left(\frac{L}{2D}\right)\right) = 0.2, \quad (1)$$

where $L = 27.6$ mm (detector size) and $D = 62$ mm (distance from the sample to the center of the detector). In this experiment, we use a sub-region of the CCD side length of around 24 mm, which leads to a $NA = 0.19$. Therefore, the theoretical resolution, defined as

$$\Delta x = \lambda \cdot D/L, \quad (2)$$

is about 38 nm for the present configuration of the RESCAN tool. In this paper, we investigate the optimization of the illumination intensity to obtain a quality image suitable for defect inspection. We used RESCAN to inspect an EUV test mask under different illumination conditions to investigate the impact of the illumination intensity on the image reconstruction quality and resolution.

Test EUV mask

The test mask structure we used is a Siemens star with 15 spokes, as shown in Fig. 1. The structure is produced in house with electron-beam lithography. The absorber is a 140 nm thick HSQ (Hydrogen silsesquioxane) layer on top of a 40 pairs

Mo/Si multilayer (ML). The used absorber material has a much longer attenuation length compared to common absorber materials such as Ni or TaBN. Thus, the absorber layer is thicker than that in standard EUV masks, which means that the current study aims to identify a general trend in the relation between image resolution and flux. An experiment with a commercial mask sample will be necessary for a quantitative evaluation of the precise flux requirement for lensless APMI.

Figure 1. SEM image of the tested EUV mask. The closed shapes are the absorber (HSQ 140nm), while the rest is the ML surface.

RESCAN relies on ptychography, a scanning coherent diffraction imaging technique, to retrieve the complex amplitude of the mask. The first step in the ptychography imaging process is to record EUV diffraction patterns for a specific exposure time at multiple positions. In our setup, we move the sample and collect images of the diffraction intensity with a CCD detector. The intensity distribution on the CCD is degraded away from the center to the edge because the CCD surface is flat, which leads to the optical path differences between a probe to different pixels. Typically this degradation can be corrected computationally [5]. However, in this study, we ignored it to avoid adding any bias in the image reconstruction quality.

In order to increase the intensity of the higher-order diffraction, we employ the high dynamic range (HDR) imaging process. The diffraction patterns are recorded with different exposure times and recombined to increase the image intensity range. High exposure images are used for the lowest intensity areas of the diffraction pattern, and low exposure images are used to fill in the portions of the diffraction pattern with saturated pixels or bleeding effect. Figure 2 shows images with 9 different single exposure times from 0.05 to 40 seconds. The pixel number of the image after cropping is 1800×1800 , where the detector pixel size is $13.5 \times 13.5 \mu\text{m}^2$.

Figure 2. The diffraction patterns were recorded by a CCD with 9 different single exposure times. (a) 0.05, (b) 0.1, (c) 0.5, (d) 1, (e) 2, (f) 5, (g) 10, (h) 20, and (i) 40 seconds. The photon flux is about 10^9 photons/s.

In order to study the effect of the exposure time on the reconstruction image quality and resolution, we used the original data to synthesize 9 different HDR datasets with increasing exposure times and we labeled them with the number of the single-exposure images used, N ($N=1,2,3,\dots,9$). For example, “ $N=2$ ” corresponds to an HDR image synthesized with two images of Fig. 2(a) and 2(b), “ $N=3$ ” corresponds to an HDR image synthesized with three images of Fig. 2(a), 2(b) and 2(c). The synthesized HDR images are shown in Fig. 3. For convenience, in some figures and text, we use the maximum exposure times (t_{Max}) to indicate the HDR diffraction data set. For example, an HDR image with $N=1$ corresponds to the $t_{\text{Max}} = 0.05$ s. $N=2$ corresponds to the $t_{\text{Max}} = 0.5$ s, and so on. The photon flux of the beam in this experiment is about 10^9 photons/s. Therefore, the approximate illumination photon count to obtain the HDR images is defined with the equation, $\sum_{n=1}^N t_{\text{exp},n}$, and goes from 5×10^7 (for $t_{\text{Max}} = 0.05$ s) to 1.09×10^{11} (for $t_{\text{Max}} = 40$ s).

Figure 3. The HDR processed diffraction images using the images in Fig. 2. (note that the images' contrast and brightness are increased to show and to compare the pattern's details)

2. RESULTS AND DISCUSSION

Reconstruction comparison

We used the regularized PIE algorithm (rPIE) as the reconstruction method [6]. The rPIE algorithm uses two regularization parameters, α and β , to control the update of the object and the probe, respectively. Here we set $\alpha = 0.1$, $\beta = 0.9$. The probe update started after 50 iterations, and the total iteration number was set to 1000.

The test EUV mask is reconstructed using the HDR processed diffraction data sets, as shown in Fig. 3. The images in Fig. 4 (1-3) show the amplitude, phase, and unwrapped phase images using three different t_{Max} . For different t_{Max} , we obtained images of the amplitude (abs) and phase (ang) from the complex amplitude we reconstructed. The unwrapped phase image (uwrp) is created by unwrapping the phase resulting in an image with a continuous angle range, while the phase image is limited in the $\pm\pi$ range. in Fig. 4(1-3), the t_{Max} values are 0.05, 5, and 40 s respectively. The sharpness of the reconstructed object increases with the t_{Max} in the amplitude, phase, and unwrapped phase images.

Figure 4. The amplitude (abs), phase (ang) and unwrapped (uwrp) images of the reconstructed object using different HDR image sets (1) $t_{\text{Max}} = 0.05\text{ s}$ (2) $t_{\text{Max}} = 5\text{ s}$, and (3) $t_{\text{Max}} = 40\text{ s}$.

The *Fourier error* is the the difference of measured diffraction and update Fourier transformed exit wave during the iterations. The error curve also shows the convergence rate of the reconstruction procedure and is defined as:

$$\text{Fourier error} = \frac{\sum_q \sum_{ij} |\sqrt{I_{ij}} - |F(\Psi_{ij})||}{\sum_q \sum_{ij} 1}, \quad (3)$$

where I is the intensity of the measured diffraction pattern on the detector, ψ is the exit-wave and F is the Fourier transform operator. The Fourier error is summed over all pixels (i, j) and averaged over the scan positions q [7]. Using this metric, it is found that the error is reduced as a function of the exposure times. The most significant improvement is observed between 0.05 s and 0.5s, as shown in Fig. 5

Figure 5. The Fourier errors in the rPIE reconstruction. The multiple error curves are relative to different HDR image sets.

We investigate the image contrast and the edge sharpness as indicators of the reconstruction resolution and quality. We considered the red circle shown in the reconstructed images in Fig. 4 which has a radius of R . The pitch of the grooves in the Siemens Star increases continuously as a function of the distance from the center and, for a radius of R , it is $2\pi R/15$. We extracted the intensity profile along the circle from amplitude, phase, and unwrapped phase images. The profiles are processed with a low-pass filter (lpf) as shown in Fig. 6 (1) and with sine fitting (sf) as shown in Fig. 6 (2). The values on the x-axis of Fig. 6 are integer numbers marking the position of the grooves along with the profile. The absolute value (abs.) corresponds to the amplitude of the reconstructed image. The angle (ang.) is the phase of the reconstructed image. We added a π offset to the phase to make it positive throughout the profile length. Since the phase obtained from the

reconstruction procedure is limited to the $\pm\pi$ range, we used a phase unwrapping procedure to obtain continuous angle maps.

In Fig. 6 (1), the cross-section data and the relative low-pass filtered curves are plotted for an HP of 144 nm and $t_{\text{Max}}=40$ s. Here we choose HP = 144 nm, for which we have obtained the cross-sections of all the images including amplitude, phase and unwrapped images as well as the processed signals with a low-pass filter and sine fitting. Despite the optimization of the filtering and fitting process, the processed peaks or valleys are shifted due to several reasons. First, by defining the central positions of the circle, the grooves can be shifted within the given axis and grid. Moreover, due to the off-axis optical path, the reconstructed Siemens star is not perfectly symmetric in isotropic direction, resulting in the position shift of the grooves. The 15 peaks of the angle and the unwrapped phase image are more clearly visible than those of the absolute values. Fig. 6 (2) shows the same cross-section data in Fig. 6 (1) but with the sine fitting. In both cases of lpf and sf, the phase data including the unwrapped phase data are affected less by the reconstruction artifacts. Therefore, the phase data is more beneficial for our purpose.

Figure 6. (1) The cross-section data of the reconstructed images at a period of $hp = 144$ nm, the low-pass filtered data, and the derivative of the filtered data. **(2)** cross-sections of the reconstructed images at a period of $hp = 144$ nm, sine-fitting of the data, and the derivative of the fitted data.

Contrast vs. exposure time

Those data obtained from Fig. 6 are used to create contrast curves, as shown in Fig. 7. The contrasts of the low-pass filtered data and sine fitted data are calculated with the equation as follows.

$$\text{contrast} = \frac{|I_{\max} - I_{\min}|}{|I_{\max} + I_{\min}|}, \quad (4)$$

In Fig. 7, the contrasts of the 15 grooves from Fig. 6 are averaged, and the standard deviation from 15 grooves is obtained. The curves are plotted as a function of the $t_{\max}$ for both phase and unwrapped phase images. The curves reached the maximum at around 2-5 seconds and then converged. This trend is shown similarly with both phase and unwrapped phase images. The amplitude contrast curve is not shown in Fig. 7 because of its inconsistent behavior against the phase data.

Figure 7. The contrast curves were obtained from Fig. 6 for (a) phase and (b) unwrapped reconstructed images. The contrasts are compared with both low-pass filtered and sine-fitted in Fig. 6. Furthermore, their standard deviation (std.) is added.

Derivatives vs. exposure time

We also calculated the derivatives of the low-pass filtered data and sine fitted data displayed in Fig 6. The maxima of the derivative correspond to the edges in the reconstructed image, and indicate the sharpness of the reconstructed features. The 15 spokes of the Siemens star structure generate 30 peaks and valleys as shown in Fig. 6. The derivatives average for each of the 9 different HDR cases for the amplitude, phase, and unwrapped phase profiles are shown in Fig. 8. The derivatives of both low-pass filtered data and sine fitted data are shown as a function of the $t_{\max}$. All the curves increase quickly from 0.05 seconds to 5 seconds, but do not show any significant improvement for higher exposure values. This suggests that exposure times above 5 seconds do not significantly improve the image resolution.

Figure 8. The averaged derivatives of the data from Fig. 6 as a function of t_{Max} for (a) lpf and (b) sf. (The blanks tick labels are 0.05, 0.5, and 1 from left).

In the same way as above, we calculated the derivatives of the profiles with different pitches generated by changing the radius of the contour circle. We considered half-pitches from 201 nm down to 72 nm. As shown in Fig. 9, a comparable trend is seen through all the pitches. The curves increase significantly from 0.05s to 5 s, but remain approximately constant for higher exposure times. The values reach a maximum of around 2-5 seconds. However, in the case of $hp = 72$ nm, the derivatives increase continuously. This suggests that a smaller pitch requires a longer exposure time to get properly resolved. In the half-pitch range from 201 nm to 122 nm, the curve is downward above around 5 s, while the half-pitch range below 93 nm to 72 nm, the curve is right slopping above around 5 s.

Figure 9. Derivatives of the low-pass filtered amplitude, phase, and unwrapped-phase data as a function of exposure time for different pitches in Siemens star. ((The blanks tick labels are 0.05, 0.5, 1 and 2 from left).

In summary, we estimate a trend of the image quality related to exposure times and the structure's pitch. The optimal t_{Max} to produce HDR image sets is obtained for the given EUV mask sample. The exposure times have to be controlled efficiently for a target pitch according to the contrast or derivatives curves. For the sample we used in this work, the image quality reaches a stable value for an exposure time of 5 s. However, for smaller pitch structures (below 93 nm in this paper),

the image quality increases continuously in the test exposure time range (below 40 s). Further study can estimate the trend for more general cases of the flux–resolution relation, for example, with different mask patterns or mask layer stacks.

3. CONCLUSIONS

Accurate metrology of the EUV mask is essential in EUV lithography. We investigated the optimization of the illumination intensity to obtain a high-quality image and, therefore, to improve the defect sensitivity. We analyzed the reconstructed images to estimate the relation between the maximum exposure time and the resolution in the reconstructed image. We analyzed cross-sectional data of a Siemens star for different pitch sizes. The measured data are processed with different filtering or fitting methods, then the contrast and derivative curves are studied as a function of the exposure time or pitch. The analyzed data shows that the image quality reaches a stable value for exposure times of 2 to 5 s. The optimal exposure times are dependent on the target feature size and the closest we get to the theoretical resolution limit, the higher the required exposure time becomes. The most efficient exposure time can be estimated with the contrast and derivated curves. In order to generalize these results, further tests with different features and layouts of the EUV mask will be necessary.

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