Enhancing native defect sensitivity for EUV actinic blank inspection: optimized pupil engineering and photon noise study

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ABSTRACT

In this paper, we discuss the impact of optimized pupil engineering and photon noise on native defect sensitivity in EUV actinic blank inspection. Native defects include phase-dominated defects, absorber defects, and defects with a combination of phase and absorption behavior. First, we extend the idea of the Zernike phase contrast (ZPC) method and study the impact of optimum phase shift in the pupil plane on native defect sensitivity, showing a 23% signal-to-noise ratio (SNR) enhancement compare to bright field (BF) for a phase defect with 20% absorption. We also describe the possibility to increase target defect SNR on target defect sizes at the price of losing the sensitivity on smaller (non-critical) defects. Moreover, we show the advantage of the optimized phase contrast (OZPC) method over BF EUV actinic blank inspection. A single focus scan from OZPC has better inspection efficiency over BF. Second, we make a detailed comparison between the phase contrast with apodization (AZPC) method and dark field (DF) method based on defect sensitivity in the presence of both photon shot noise and camera noise. Performance is compared for a variety of photon levels, mask roughness conditions, and combinations of defect phase and absorption.

Keywords: EUV Actinic Mask Inspection, Native Defect, Zernike Phase Contrast Microscopy, Pupil Engineering, Optimum Phase Shift. Apodization, Photon Shot Noise.

1. INTRODUCTION

As EUV lithography marches towards high-volume manufacturing, the defectivity of EUV mask blanks is still an issue that needs to be addressed [1]. For actinic blank inspection, not just the multilayer defects which mostly show phase defect behavior need to be identified with high sensitivity, but also amplitude defects and defects with a combination of phase and amplitude behavior need to be captured. Therefore, a general solution for all potential types of defects on the EUV mask is needed to further improve the inspection efficacy of actinic inspection systems.

To identify phase-dominated multilayer defects on EUV mask blanks, ZPC and DF inspection tools have both been studied and demonstrated [2, 3]. Results show the capability to have high defect sensitivity on critical defects for advanced technology nodes. However, in order to take both amplitude and hybrid amplitude/phase defects into consideration, our previous study shows an optimum phase shift is needed to have acceptable defect sensitivity simultaneously for all types of defects [4]. Also, the impact of system noise on defect SNR needs a detailed study to evaluate the inspection performance of OZPC compared to conventional methods [5].

In this paper, a simulation study of OZPC for native defect inspection and the impact of photon noise on defect sensitivity is presented. First we show the advantage of optimum phase shift in the pupil plane to tune both the peak signal and speckle noise defocus position to enhance target defects sensitivity. Second, we compare the native defect SNR performance between AZPC and DF with shot noise and camera noise under various photon levels and mask roughness conditions.

2. BACKGROUND

2.1 Optical principle for optimum phase shift

Unlike the original ZPC as shown in Figure 1a, which utilizes a 90° phase shifts to form intensity modulation between

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unscattered background light and the scattered light from phase defect; the OZPC is targeted for defects with hybrid behavior. As shown in Figure 1b, the 90° phase shifts on unscattered background light not aligned with the scattered light from hybrid defects; therefore, a more optimum phase shift is needed to achieve better image contrast as shown in Figure 1c.

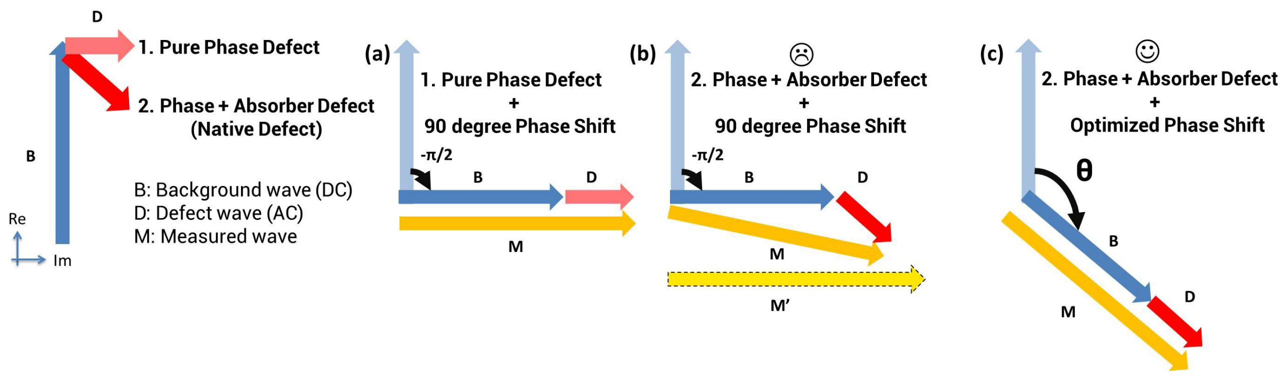

Figure 1. Phasor diagram for native defect: (a) 90° phase shifts with phase defect. (b) 90° phase shifts with hybrid defect. (c) Optimum phase shift with hybrid defect.

2.2 Defect SNR calculation

Defect sensitivity in defect inspections is characterized through the concept of SNR. In a simplified model, we calculate the defect SNR as defect signal divided by the standard deviation of the intensity resulting from mask scatter noise and "system noise" to account for the noise generated by other sources. In order to have a detailed study of defect SNR in an EUV actinic mask inspection system, we consider "system noise" to be dominated by photon shot noise present in both the background intensity and defect signal and additionally the camera noise from typical EUV CCD camera. In this study, we take the photon level into account normalized to the value corresponding to the bright field background intensity. Thus we can calculate the defect SNR based on the absolute value of photons. The defect SNR calculation is based on the equation shown below:

SNR =

$$\frac{Signal \times Photon}{\sqrt{Background \times Photon + Signal \times Photon + Camera\_Noise + (std(roughness) \times Photon)^2}} \quad (1)$$

3. SIMULATION RESULTS

3.1 Simulation parameters and settings

We use a thin mask imaging model to simulate both signal and noise levels. We model defects as Gaussian phase profiles. The defect peak height we consider ranges from 0.5 nm to 1.5 nm, and the full width at half maximum (FWHM) ranges from 10 to 100 nm on the mask. For intensity absorption we consider ranges from 0% to 100% to represent pure phase defect to pure absorption defect. The radius of the absorption region is assumed to be 2-sigma (standard deviation) of the Gaussian profile, which means 95% of the defect area is covered by a step absorption function. For speckle, we consider mask roughness ranging from 50 pm to 100 pm, with correlation length about 100 nm. For imaging conditions, we assume an NA of 0.2 at the mask and disk illumination with a sigma value of 0.5. The phase shift in the pupil plane ranges from 0° to 180° with a shape matching that of the disk illumination. The apodization is 10% intensity transmission for AZPC in the photon noise study and 0% intensity transmission for the DF. Reference photon levels range from 100 to 10,000 photons as bright field background intensity for photon noise study. In considering photon and camera noise with the above normalization, we assume the physical pixel size does not to affect the imaging performance. For example, in SHARP the physical pixel size is 15 nm at the mask and 13 um at the CCD. Figure 2 shows the schematic diagram of the defect and the illumination settings.

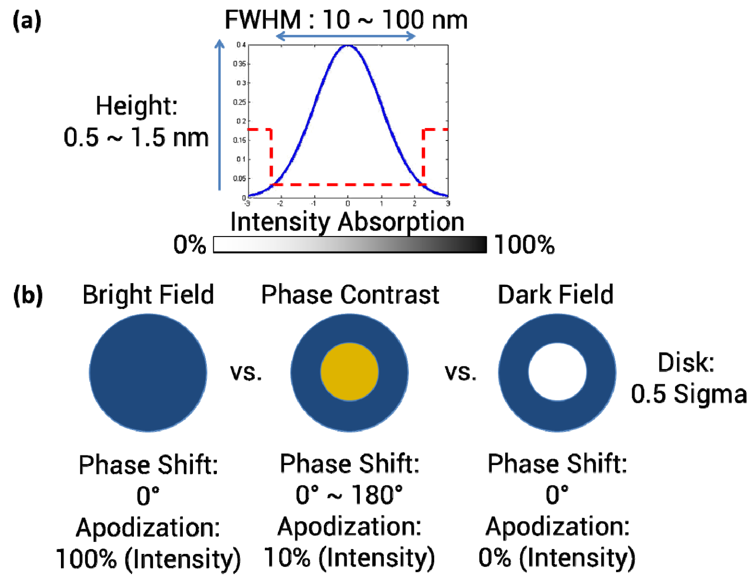

Figure 2. Schematic diagram: (a) native defect, red dash line indicates the absorption function which covers 95% of the defect. (b) Pupil function for BF, AZPC, and DF used in the simulation.

3.2 The impact of phase shift in pupil plane on defect sensitivity

In this part of the discussion, we consider the pupil with phase shift only without apodization to understand the impact of optimum phase shift on native defect sensitivity. Figure 3a shows the defect signal through-focus behavior under various phase shifts in the pupil plane for a phase defect with 30% absorption. With 90° phase shifts, the peak defect signal is away from the best focus due to the absorption in the defect. As the phase shift varies, the defect through-focus behavior can be adjusted to increase defect sensitivity at focus. At the same time, the phase-dominated speckle noise at focus decreases as shown in Figure 3b. Therefore, the difference between the nature of defect and speckle is the key reason an optimized phase shift can increase defect signal and reduce the speckle noise simultaneously.

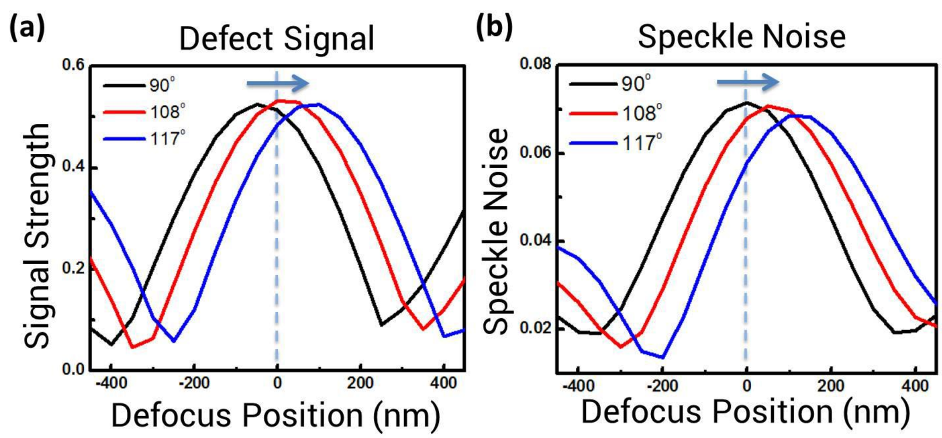

Figure 3. (a) Defect through-focus behavior under various phase shifts: 90° (Black), 108° (Red), and 117° (Blue). The defect is phase defect with 1 nm height, 60 nm FWHM, and 30% absorption. (b) Speckle noise through-focus behavior under various phase shifts: 90° (Black), 108° (Red), and 117° (Blue). The mask roughness is 77 pm with a 100 nm correlation length.

The impact of phase contrast is different from simply operating at a defocus position by BF. As we mentioned in our previous study, the peak defect sensitivity is higher with ZPC than BF in any defocus position [1]. Moreover, the impact of ZPC is shape independent. The results shown in Figure 4 indicate the peak defect signal defocus position for various defects. Figure 4b shows that the best defocus position to maximize defect sensitivity is defect-width dependent for BF. Therefore, there is no single defocus position that can work for every defect, while the ZPC shows a consistent peak signal position as defect shape varies. This result indicates that a single focus scan by ZPC is a better inspection strategy over BF even at a defocus positions.

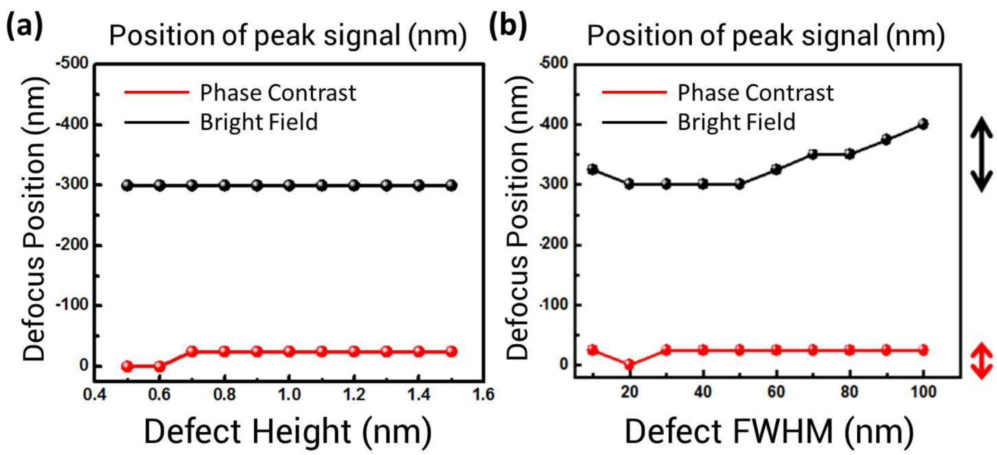

Figure 4. (a) Phase defect peak signal position under BF (Black) ZPC (Red). Defect height ranges from 0.5 nm to 1.5 nm and defect FWHM is 60 nm. (b) Phase defect peak signal position under BF (Black) and ZPC (Red). Defect FWHM ranges from 10 nm to 100 nm and defect height is 1 nm.

Instead of maximizing the defect signal, maximizing the defect SNR requires a different optimum phase shift. As shown in Figure 5, the trends of signal and noise are different due to the nature of the defect and mask roughness, leading to an optimum phase shift for defect SNR at 117°. For the defect with 20% absorption, an optimum phase shift can achieve a 23% SNR enhancement compare to BF. Moreover, for a set of defects with different absorptions as shown in Table 1, an optimum phase shift can be chosen to increase target defects sensitivity at the price of losing the sensitivity on phase dominated defects. With 126°, defects with absorption values of 20%, 30%, and 40% can have defect SNR enhancement: 2%, 6%, and 14% respectively, while defects with absorption less than 20% have reduced defect SNR. This illustrates the possibility of utilizing the difference in the absorption of the defect to amplify the SNR of defects with absorption in a targeted range at focus.

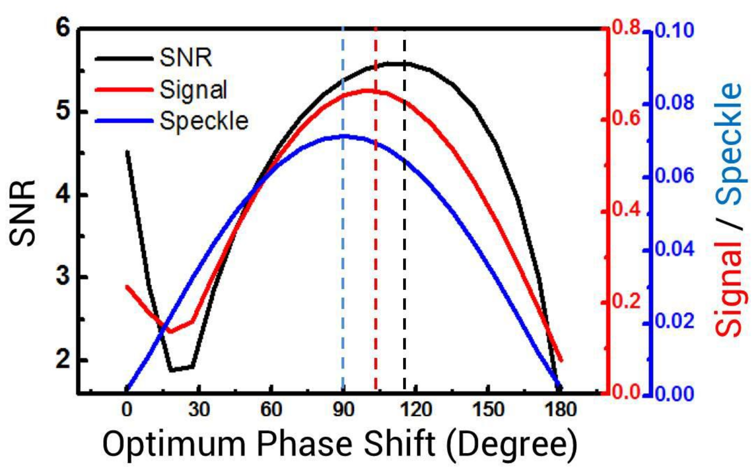

Figure 5. Defect signal (red), speckle noise (blue), and defect SNR (black) under various phase shifts. Defect height is 1 nm and defect FWHM is 60 nm. Defect absorption is 20%. The mask roughness is 77 pm with a 100 nm correlation length. The system noise is 5%.

Table 1. Defect signal and SNR enhancement at 126° compare to 90° situation for defects with different absorption: 0% ~ 40%. Defect height is 1 nm and FWHM is 60 nm. The mask roughness is 77 pm with a 100 nm correlation length. The system noise is 5%.

Stronger Absorption →

90° → 126°	0%	10%	20%	30%	40%
ΔSignal	-14%	-12%	-9%	-5.5%	+1.2%
ΔSNR	-3%	-1%	+2%	+6%	+14%

3.3 The impact of photon noise on inspection efficiency for native defects

As discussed in the previous section, a single focus scan with optimum phase shift has better defect SNR relative to BF operating with defocus. In this section, we compare phase contrast with apodization (AZPC) to DF from the perspective of defect SNR.

Figure 6 shows the comparison between AZPC and DF on a pure phase defect. The quantity ratio shown in the figure is defect SNR ratio between AZPC and DF. AZPC has better performance than DF when the ratio is larger than 1, and DF has better performance when ratio is smaller than 1. For a pure phase defect with a mask roughness at 75 pm, AZPC operating at 162° phase shifts shows better performance when the photon level normalized to the clear field defect free image intensity of less than 2000 photons, while DF is better on the other end. As mask roughness decreases, the advantage of AZPC extends to higher photon level. AZPC is the more favorable techniques with 4000 input photons if mask roughness is 50 pm, and AZPC is the favorable technique with 1000 input photons if mask roughness is 100 pm.

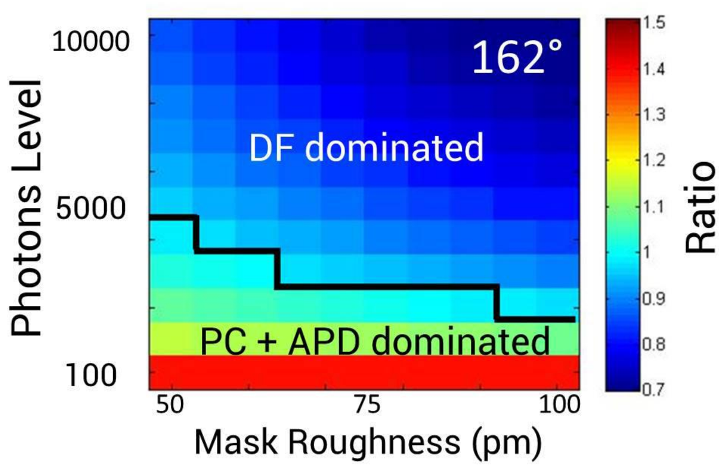

Figure 6. Phase defect SNR comparison between AZPC and DF under various photon levels and mask roughness conditions. AZPC is operated under 162° phase shifts and 10% apodization in the pupil plane. Defect height is 1 nm and defect FWHM is 60 nm with 0% absorption. Ratio > 1 indicates AZPC has better defect SNR.

To explain the transition from DF to AZPC as the photon level decreases, we have to look into the detail of Equation 1 for both methods. Signal ratio is the ratio of the numerators in Equation 1 between AZPC and DF, and noise ratio is the ratio of the denominators in Equation 1 between AZPC and DF. A signal ratio larger than 1 means AZPC has stronger defect signal relative to DF. A Noise ratio larger than 1 means AZPC has larger noise relative to DF. If the noise ratio is larger than 1 and signal ratio is 1, it means that DF has better defect SNR relative to AZPC. If the noise ratio is the same as signal ratio, it means that both methods have the same defect SNR. The signal ratio stays as constant when the photon level drops, while the noise ratio is determined by the photon level.

Figure 7 shows the noise ratio between AZPC and DF for a mask roughness at 61 pm. For a pure phase defect with the height is 1 nm and the FWHM is 60 nm, the signal ratio is 1.47. It means AZPC has a defect signal 47% stronger than DF. The defect signal ratio between the two methods determines the transition point of which techniques has better defect SNR. DF has better defect SNR when the noise ratio is larger than 1.47, and AZPC has better defect SNR when the noise ratio is smaller than 1.47. Figure 7 shows that the noise ratio between AZPC and DF is reduced as photon level drops while the signal ratio stays as constant. This explains why AZPC is better at low photon level and DF is better at high photon level, and the transition point is determined by the signal strength difference between these imaging techniques and the mask roughness conditions.

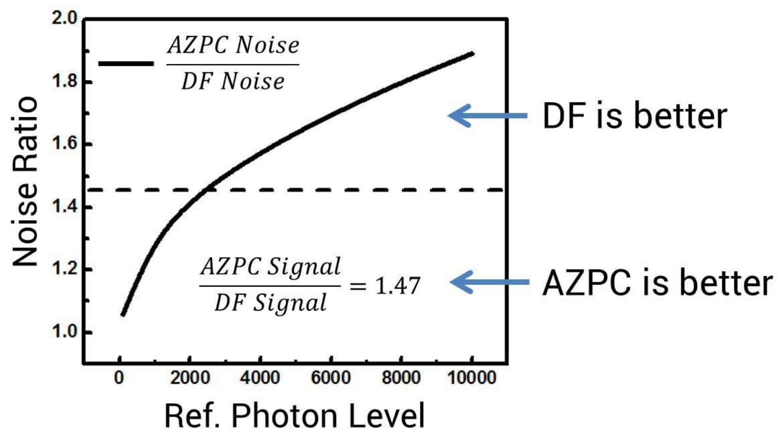

Figure 7. Noise ratio between AZPC and DF under various photon levels. Dash line indicates the target defect signal ratio between AZPC and DF. The target defect is pure phase defect with 1 nm height and 60 nm FWHM. The mask roughness is 61 pm. AZPC is operated at 162° phase shifts and 10% apodization in the pupil plane.

In order to have an acceptable detection rate with low false positive on defect inspection, sufficiently high SNR is needed. For EUV actinic blank inspection, the defect SNR should be approximately 10 or larger. Therefore, there is a minimum photon level in the inspection system as the defect SNR drops with reducing photon levels. As shown in Figure 8, for a pure phase defect with a mask roughness level of 61 pm, DF needs at least 960 photons to have defect SNR about 10, while AZPC only needs 775 photons. The result is due to stronger single strength from AZPC relative to DF. This translates to a 20% relaxation of the source power requirement.

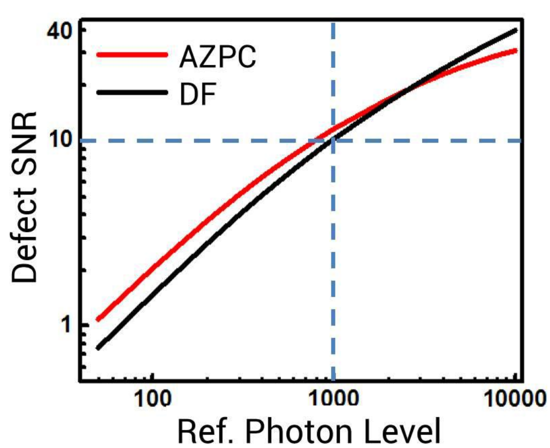

Figure 8. Defect SNR at different photon levels by AZPC (red) and DF (black). The pure phase defect height is 1 nm and FWHM is 60 nm. The mask roughness is 61 pm with correlation length at 100 nm. AZPC is operated at 162° phase shifts and 10% apodization in the pupil plane.

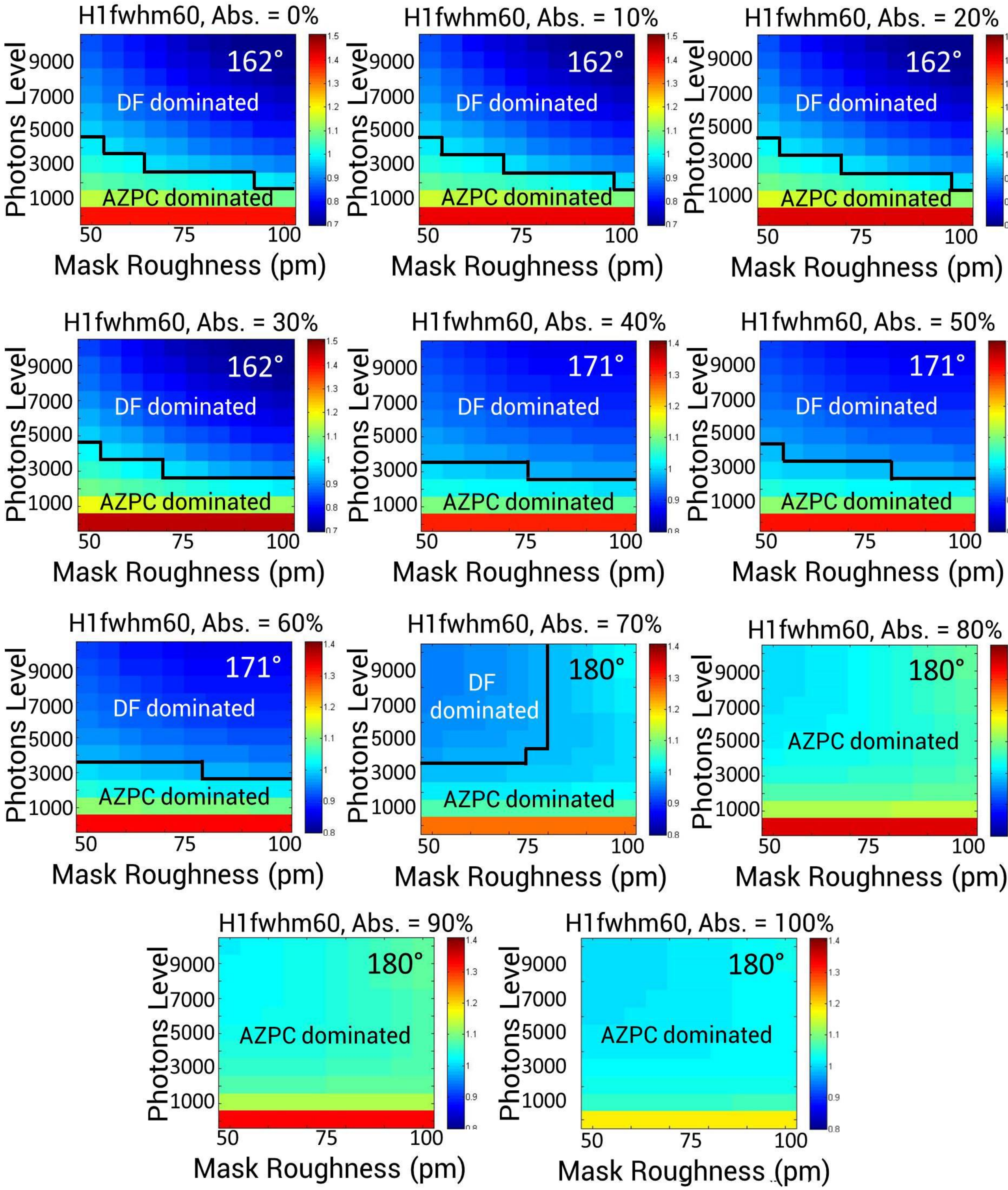

Figure 9. Defect SNR comparison between AZPC and DF with different defect absorptions, ranging from 0% to 100%. The defect height is 1 nm and FWHM is 60 nm. The mask roughness ranges from 50 to 100 pm with correlation length at 100 nm. The photon level ranges from 100 to 10,000 photons. AZPC is operated at optimum phase shift for each defect, indicating by the angle shown in each figure.

Figure 9 shows the defect SNR comparison between AZPC and DF for defects with different absorption, covering a range from pure phase defect to pure amplitude defect. As the defect absorption component increases, the advantage of AZPC is more obvious and extends to higher photon levels. For pure phase defect, AZPC is a better solution when photon level is less than 3000 photons. For phase defect with 50% absorption, the boundary extends to less than 4000 photons. For defects with more than 80% absorption, AZPC is better than DF in all the photon levels and mask roughness conditions we are interested in. This result shows the possibility of utilizing AZPC for actinic blank inspection, covering from phase defects to absorber defects with a single focus scan with high defect sensitivity.

4. CONCLUSION

We discussed the possibility of utilizing pupil engineering to enhance native defect sensitivity for EUV actinic blank inspection. Native defects are usually a combination of phase and amplitude object. Thus simply using BF or DF for defect inspection cannot cover all types of defects on EUV masks. The phase shift in the pupil plane can adjust the defect through-focus behavior based on the nature of the defect. An optimum phase shift can increase defect SNR by increasing defect signal and lowering the speckle noise at the same time. A 23% defect SNR enhancement compared to BF is achieved for a phase defect with 20% absorption. Moreover, the selection of optimum phase shift can help us increase defect sensitivity on target range of absorption defects at the price of losing sensitivity on smaller (non-critical) ones. With the consideration of photon shot noise from signal and background, speckle noise, and camera noise in an inspection system, AZPC shows the possibility to have better defect SNR over DF for phase defect inspection under low photon levels. AZPC has higher defect SNR than DF for a pure phase defect with a mask roughness of 61pm when the photon level is less than 2000. AZPC also has lower operation photon limit (defect SNR $\geq$ 10) compare to DF for phase defect inspection. This is due to the fact that AZPC has larger defect signal over DF and the difference in the noise level decreases as photon level decreases. Moreover, the dominance of AZPC extends to higher photon levels as defect absorption increases. The results show the possibility to apply this idea not just on actinic blank inspection, but also on actinic pattern mask inspection [6].

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