Computational Study of the Focus Monitoring with Sub-Wavelength Grating in Optical Lithography

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A feasibility study of the focus monitoring method with sub-wavelength grating is computationally performed. Instead of non-180° phase shifter which is commonly used for focus monitors, sub-wavelength grating with depth of 180° phase shifter is adopted to produce effective non-180° phase shifting. The result shows that the 180° sub-wavelength grating successfully produces an asymmetric light intensity distribution on wafer with both on-axis and off-axis illuminations in a same manner as typical focus monitors with 90° phase shifter. This indicates that the sub-wavelength grating is a focus monitoring pattern which can be embedded on standard phase shift masks with 180° phase shifter contrary to commonly used phase shift focus monitors.

Keywords: Optical lithography, Focus monitoring, Phase shift focus monitor, Alternating phase shift mask, FDTD simulation

1. Introduction

In optical lithography for semiconductor manufacturing, focus control is one of the most important aspects of process control to ensure required imaging quality. Among several focus monitoring methods proposed so far [1–8], Phase Shift Focus Monitor (PSFM), developed by Brunner in IBM [1,2] has been widely used for a quarter of a century [9-11]. Recent report [12] indicates that this technology may still work on EUV lithography. PSFM utilizes the phase edge technique. The fundamental structure of the pattern of PSFM is similar to an isolated line of Alt-PSM, but the phase shifter is 90° instead of 180°. This structure produces an aerial image with a focus-dependent asymmetry. The asymmetry induces lateral image shift with its focus level to be printed. By deploying the patterns of lines and shifters into suitable bar-in-bar or box-in-box structures, we can use commercial overlay metrology tools to measure the shift.

Instead of non-180° grooves, it is theoretically possible to produce effective non-180° phase shift by using sub-wavelength grating with 180° grooves [13]. The principle behind the effective phase shifting effect with this sub-wavelength grating is that for such a sub-wavelength features, spatially averaged electromagnetic properties are printed due to the resolution limit. The amount of the effective phase shifting produced by the sub-wavelength grating is approximately estimated by its duty cycle (the ratio of the area of grooves in the phase shifting area to the entire phase shifting area); however, it also depends on the shape of the grooves and the polarization of the illumination light [14].

In this study, we have numerically investigated the feasibility of the focus monitoring method that utilizes the focus-dependent asymmetry of the light intensity distribution produced by sub-wavelength grating and explored the possibility of focus monitoring with a conventional Alt-PSM in combination with both on-axis and off-axis illuminations.

2. Simulation model

Figure 1 shows the schematics of both fundamental PSFM pattern (a) and the one we investigated in this study (b). The PSFM pattern consists of the line centered with 90° phase shifting. Instead of non-180° grooves, it is theoretically possible to produce effective non-180° phase shift by using sub-wavelength grating with 180° grooves [13]. The principle behind the effective phase shifting effect with this sub-wavelength grating is that for such a sub-wavelength features, spatially averaged electromagnetic properties are printed due to the resolution limit. The amount of the effective phase shifting produced by the sub-wavelength grating is approximately estimated by its duty cycle (the ratio of the area of grooves in the phase shifting area to the entire phase shifting area); however, it also depends on the shape of the grooves and the polarization of the illumination light [14].

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area on its one side. The phase shifting area on the reticle is typically trenched by the depth of 90° of the wavelength of the illumination light. While, the pattern of the sub-wavelength grating focus monitoring (SWG-FM) employs sub-wavelength 180° trenched and non-trenched features instead of the large 90° trench in PSFM. The duty cycle of this phase shifting area is defined as \( \frac{g_1}{g_1 + g_2} \) and the amount of the effective phase shifting of this area depends on the duty cycle. The lateral pattern shift behavior of these focus monitoring patterns shown in Fig. 1 was numerically investigated in this study. The illumination light was assumed to be perfectly coherent and it perpendicularly incidents to the patterns or incidents with incident angles ±\( \phi \) along with the plane perpendicular to the line with width \( w \) in the focus monitoring patterns. Hereinafter, the incident angle of the illumination light is represented as \( \sigma = \sin \phi \).

The light propagation through the focus monitoring patterns on the masks were calculated with finite difference time domain (FDTD) method with CST Studio Suite from Dassault Systems, and the aerial images on wafer was calculated from the obtained electromagnetic field on the surface of the focus monitoring patterns with in-house developed code. Through the study, the parameters and physical properties of the masks were defined as follows unless specified otherwise: \( w = \frac{3}{4} \lambda \), \( g_1 = g_2 = \frac{1}{4} \lambda \), \( d_1 = 2d_2 = \frac{1}{2} \lambda \), refractive index of the mask blank \( n = 1.5 \), where \( \lambda \) is the wavelength of the illumination light.

### 3. Results and discussion

#### 3.1. Lateral pattern shifting behavior

The calculated aerial images of the focus monitoring patterns of PSFM and SWG-FM at various focus offsets are shown in Figs. 3 and 4 respectively. As a reference, the corresponding aerial image of ideal 2D mask with perfect 90° phase shifter and transmittance is also shown in Fig.
2. The focus offsets (FO) were programmed from $FO = -1.0\lambda$ to $1.0\lambda$, and 5 focal points including the best focus (BF) were shown here. All calculations were performed with the numerical aperture (NA) of 0.65 and 0.0σ.

As shown in Figs. 3 and 4, the lateral image shift depending on the focus offset is clearly observed for both PSFM and SWG-FM. Comparing to the aerial images of 2D ideal mask shown in Fig. 2, the image of SWG-FM is rather closer to that of 2D ideal mask than that of PSFM.

Figure 5 shows the plot of the calculated amount of lateral image shift produced by PSFM and SWG-FM depending on the focus offset. The imaging light intensity threshold is assumed to be 0.35. As a reference, the calculated image shifts of ideal 2D mask is also shown in the figure. The plot of SWG-FM is close to that of ideal 2D mask simulation result even though there is small offset observed between these two plots. On the other hand, the plot of PSFM shows less sensitivity (the amount of the lateral image shift per focus offset) and linearity than that of SWG-FM.

This difference of the sensitivity and linearity can be explained from the difference of the aerial images of both focus monitors shown in Figs. 3 and 4. Contrary to the aerial images of SWG-FM and ideal 2D mask, the aerial images of PSFM shows noticeable asymmetric about the focus offset. This asymmetry comes from well-known image imbalance which is an inherent characteristic of Alt-PSM originated from light scattering at the edge of the trench structure of the phase shifter [15]. In case of SWG-FM, the edge effect is not significant because the properties of the sub-wavelength features are electromagnetically averaged on the
imaged wafer.

3.2. Numerical aperture dependency

Figure 6 shows the plot of calculated amount of lateral image shifting with 0.45 NA. Comparing to that of 0.65 NA shown in Fig. 5, the plot of SWG-FM is almost overlapped to that of ideal 2D mask, while there is huge offset observed between PSFM and the others due to the image imbalance, even though its linearity is relatively maintained in this case.

Fig. 6. The plot of the calculated amount of lateral image shifting produced by PSFM and SWG-FM depending on the focus offset with NA of 0.45. The imaging threshold is 0.35.

Figures 7 and 8 show the plots of calculated amount of lateral image shifting with 0.85 and 0.95 NA respectively. In principle, the sensitivity of PSFM tends to be improved but the linearity tends to be degraded as NA increases as shown in the plot of ideal 2D mask simulations in both figures. SWG-FM reproduces the behavior predicted by the ideal 2D mask simulation, while the difference of PSFM from the other two obvious as shown in Figs. 7 and 8. Especially in case of 0.95 NA, PSFM image was not able to be printed at the imaging light intensity threshold of 0.35 even at best focus.

Thus, NA dependency of SWG-FM is well predicted by ideal 2D mask simulation, while 3D mask simulation is absolutely required to understand the behavior of PSFM.

3.3. Illumination light incident angle dependency

Figures 9, 10, and 11 show the plots of calculated amount of lateral image shifting produced by PSFM and SWG-FM in combination with off-axis illumination with incident angle of 0.10σ, 0.20σ, and 0.30σ respectively. As shown in the plot of ideal 2D mask simulations in these figures, the sensitivity of PSFM decreases and turns to be opposite direction as the light incident angle increases.

Fig. 7. The plot of the calculated amount of lateral image shifting produced by PSFM and SWG-FM depending on the focus offset with NA of 0.85. The imaging threshold is 0.35.

Fig. 8. The plot of the calculated amount of lateral image shifting produced by PSFM and SWG-FM depending on the focus offset with NA of 0.95. The imaging threshold is 0.35.

It should be noted that SWG-FM follows the behavior of ideal 2D mask simulation for all investigated illumination light incident angles. This result indicates that the sub-wavelength grating still works well as a phase shifter to produce effective non-180° phase shifting with not only on-axis illumination but also off-axis illumination.
3.4. Effective phase shift and duty cycle of the sub-wavelength grating

Finally, we investigated the effective phase shifting of the sub-wavelength grating with various duty cycles. Figure 12 shows the calculated amount of effective phase shifting produced by the sub-wavelength grating with perpendicular illumination light. Here, NA is assumed to be 0.65, and the pitch of the grating is fixed as $g_1 + g_2 = \frac{1}{2} \lambda$.

It is found in Fig. 12 that the effective phase shifting is different between TE and TM polarization, and duty cycle itself (theoretical effective phase shifting indicated by dash line in the figure) especially around 50% duty cycle at which target effective phase shifting is 90°. The effective phase shifting of TE light tends to be less than the duty cycle, while that of TM light tends to be larger. The difference of the actual effective phase shifting from the estimation based on the duty cycle is around 0.1$\lambda$ at 50% duty cycle. This result suggests that SWG-FM is capable of being optimized by tuning the duty cycle to maximize the focus monitoring performance depending on the illumination condition.

4. Conclusion

We numerically investigated the feasibility of SWG-FM in combination with various NA and both on-axis and off-axis illuminations. The results indicate that the sub-wavelength grating with nominal 180° is capable of generating effective non-180° phase shifting under high NA projection system and off-axis illumination. Furthermore, the trend of lateral image shifting produced by SWG-FM is similar to
that estimated by ideal 2D mask simulation. This means that SWG-FM pattern can be optimized by using simple 2D simulation to maximize sensitivity and linearity for desired illumination condition. For further rigorous optimization, difference of the effective phase shifting from the duty cycle depending on the direction of polarization should be taken into account. Contrary to PSFM, we can employ SWG-FM on a conventional Alt-PSM and other PSMs with 180° phase shifter. Therefore, this technology can be utilized to monitor imaged focus without any specific mask, and even can be used in a production line as an inline focus monitoring tools by embedding SWG-FM pattern into device production masks.

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