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Even aberration measurement of lithographic projection system based on optimized phase-shifting marks

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ABSTRACT

In the present paper, we propose a novel method for measuring the even aberrations of lithographic projection optics by use of optimized phase-shifting marks on the test mask. The line/space ratio of the phase-shifting marks is optimized to obtain the maximum sensitivities of Zernike coefficients corresponding to even aberrations. Spherical aberration and astigmatism can be calculated from the focus shifts of phase-shifting gratings oriented at 0°, 45°, 90° and 135° at multiple illumination settings. The PROLITH simulation results show that, the measurement accuracy of spherical aberration and astigmatism obviously increase, after the optimization of the measurement mark.

1. Introduction

The projection optics system is one of the most important systems in a step-and-scan lithographic tool. Wavefront aberrations of the projections optics cause a degradation of the image quality as well as a significant reduction of process latitude of the lithographic process [1–3]. Even aberrations mainly include spherical aberration and astigmatism. Spherical aberration causes best focus position shift and isofocal tilt, and astigmatism causes a difference of the best focal positions between orthogonal lines. The even aberrations cause a reduction of usable depth of focus, and the impact of even aberrations on lithographic imaging depends on pattern size, pattern density, pattern orientation and illumination settings [4–5]. As the critical dimension shrinks, especially with the use of resolution enhancement techniques, degradation of image quality caused by even aberrations of the lithographic projection optics becomes more serious in the lithography process. To predict and minimize their adverse effects on printed patterns, the semiconductor industry calls for fast and accurate in-situ measurement techniques for measuring the even aberrations.

In recent years, a number of in situ methods for measuring the even aberrations of lithographic projection optics have been reported, such as three-beam interference [6–7], aberration ring test [8], Litel in situ interferometer [9], and transmission image sensor (TIS) at multiple illumination settings (TAMIS) [10]. Among these methods, the TAMIS is a commonly used sensor-based technique. Isolated spaces are used as a measurement mark to determine spherical aberration and astigmatism. Imaging errors are observed by focus shifts of the isolated spaces at multiple numerical aperture (NA) and partial coherence settings and measured by the TIS, which is an aerial image sensor built into the wafer stage. Using the focus shifts, the Zernike coefficients corresponding to spherical aberration and astigmatism can be calculated. The advantages of the TAMIS include robustness and speed, because it is a straightforward measurement technique that does not involve exposure of resist, and it does not rely on the formation of an intermediate image in resist which is subsequently analyzed by a scanning electron microscope, an overlay inspection tool or an optical microscope. However, binary marks on the test mask are used in the TAMIS technique, and the measurement accuracy of even aberrations can be further improved.

Recently, we have reported several novel in-situ methods for measuring the wavefront aberration based on phase-shifting marks that had a line/space ratio of 1:1 [11–13]. However, the line/space ratio of the phase-shifting marks which obviously influences the sensitivity to even aberrations was not optimized, so the measurement accuracy of even aberrations can still be further improved. In this paper, an in-situ method for measuring the even aberrations of lithographic projection optics is proposed and the

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measurement accuracy of even aberrations can obviously improve. In this method, the measurement mark on the test mask contains four phase-shifting gratings oriented at 0°, 45°, 90° and 135°. The line/space ratio of the phase-shifting gratings is optimized to obtain the maximum sensitivities to even aberrations. The Zernike coefficients corresponding to even aberrations can be extracted from the focus shifts of the imaged phase-shifting gratings at multiple NA and partial coherence settings. The measurement accuracy of even aberrations can be improved because the optimized phase-shifting gratings are more sensitive to even aberrations than the ordinary phase-shifting gratings with a line/space ratio of 1:1. Optical lithography simulation has become an indispensable tool for research, development and manufacturing. PROLITH is a well known lithographic simulator and widely used in the lithographic industry as a research and development tool, to help provide a fundamental understanding of all aspects of the lithography process, and to validate and improve the industry's theoretical understanding of lithography, and to provide a tool to the average lithographer to apply this theory to real lithography problems [14–15]. Variation ranges of sensitivities are the key factors which influence the measurement accuracy of even aberrations. Using the lithographic simulator PROLITH, the variation ranges of sensitivities of Zernike coefficients corresponding to even aberrations are calculated. The measurement accuracy of even aberrations is analyzed.

2. Measuring principle

The Zernike polynomials which represent the wavefront aberrations in the projection lenses can be expressed as [16]

$$\begin{aligned}W(\rho,\theta) &= \sum_{n=1}^{\infty} Z_n \cdot R_n(\rho,\theta), \quad n \in Z\\ &= Z_1 + Z_2\rho\cos\theta + Z_3\rho\sin\theta + Z_4(2\rho^2-1) + Z_5\rho^2\cos 2\theta\\ &\quad + Z_6\rho^2\sin 2\theta + \cdots + Z_9(6\rho^4-6\rho^2+1) + \cdots\\ &\quad + Z_{12}(4\rho^2-3)\rho^2\cos 2\theta + Z_{13}(4\rho^2-3)\rho^2\sin 2\theta + \cdots\\ &\quad + Z_{16}(20\rho^6-30\rho^4+12\rho^2-1) + Z_{21}(15\rho^4-20\rho^2\\ &\quad + 6)\rho^2\cos 2\theta + \cdots + Z_{22}(15\rho^4-20\rho^2+6)\rho^2\sin 2\theta + \cdots, \qquad (1)\end{aligned}$$

where ρ is the normalized radius of the exit pupil, and θ is the azimuthal angle. For mainstream in situ aberration measurement techniques such as TAMIS, the impact of high order spherical aberration and astigmatism on focus shifts of the aerial image of measurement mark is usually neglected. Spherical aberration can be represented by the Zernike coefficients Z_9 and Z_{16}, and astigmatism can be represented by the Zernike coefficients Z_5, Z_6, Z_{12}, Z_{13}, Z_{21} and Z_{22}, which are the coefficients of the Zernike polynomials.

In lithographic imaging, the focus shift is defined as the distance between the measured focus position and the ideal focus position. The focus position is the position at which the aerial image has the maximum light intensity. The focus shifts caused by even aberrations are functions of pupil radius and can be expressed as [10]

$$\Delta F_s(\rho) \propto Z_4 + Z_9(3\rho^2-1.5) + Z_{16}(10\rho^4-10\rho^2+1), \qquad (2)$$

$$\Delta F_a^{H/V}(\rho) \propto Z_5 + Z_{12}(4\rho^2-3) + Z_{21}(15\rho^4-20\rho^2+6), \qquad (3)$$

$$\Delta F_a^{\pm 45^\circ}(\rho) \propto Z_6 + Z_{13}(4\rho^2-3) + Z_{22}(15\rho^4-20\rho^2+6), \qquad (4)$$

where $\Delta F_s(\rho)$ is the focus shift caused by spherical aberration, $\Delta F_a^{H/V}(\rho)$ is the focus shift caused by horizontal and vertical astigmatism, and $\Delta F_a^{\pm 45^\circ}(\rho)$ is the focus shift caused by ±45° astigmatism. From Eqs. (2)–(4), the impact of even aberrations on focus shifts depend on the positions of the diffraction light of the measurement mark in the pupil.

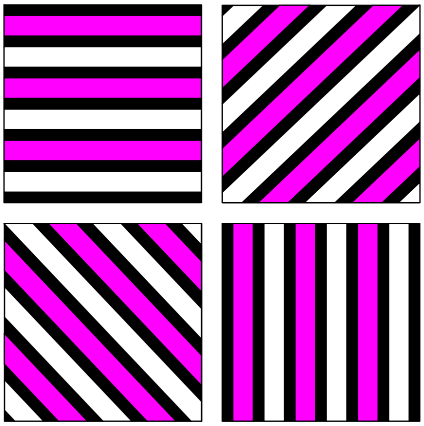

Fig. 1. Sketch map of the measurement mark.

The measurement mark used to measure spherical aberration and astigmatism in the present method is shown in Fig. 1. The mark is composed of four alternating phase-shifting gratings oriented at 0°, 45°, 90° and 135°. In optical lithography, lines can mean images of the dark regions on the mask or resist lines remaining on the wafer after development. Similarly, spaces can mean images of clear areas on the mask or resist trenches created after development. In Fig. 1, the black region represents the chrome region. The white region represents the 0° phase space and the red region represents the 180° phase space. The 0° phase space and the 180° phase space have the same width. The line/space ratio is 1:m. Take the alternating phase-shifting grating oriented at 90° as an example. The transmission function is

$$\begin{aligned}t(x) = {} & \frac{1}{2(m+1)w}\mathrm{comb}\left[\frac{x}{2(m+1)w}\right] * \left\{\mathrm{rect}\left[\frac{x+(m+1)w/2}{mw}\right]\right.\\ & \left. + e^{j\pi}\mathrm{rect}\left[\frac{x-(m+1)w/2}{mw}\right]\right\}\frac{1}{2(m+1)w}\mathrm{comb}\left[\frac{x}{2(m+1)w}\right]\\ & * \left\{\mathrm{rect}\left[\frac{x+(m+1)w/2}{mw}\right] - \mathrm{rect}\left[\frac{x-(m+1)w/2}{mw}\right]\right\}, \quad n \in Z,\end{aligned} \qquad (5)$$

where w is the linewidth of the alternating phase-shifting grating. The spectrum of the alternating phase-shifting grating is the Fourier transformation of $t(x)$ and can be expressed as

$$U(f_x) = 2jmw \cdot \mathrm{comb}[2(m+1)wf_x]\,\sin c(mwfx)\,\sin[\pi(m+1)wf_x], \quad n \in Z, \qquad (6)$$

where $f_x = \sin\theta/\lambda$ is the spatial frequency variables and the sin c function is defined as $\sin c(x) = \frac{\sin(\pi x)}{\pi x}$.

From Eqs. (2)–(4), the focus shifts caused by even aberrations depend on the positions of the diffraction light of the measurement mark in the pupil. The maximum focus shift caused by Z_9, Z_{12}, Z_{13} occurs at $\rho = 1$, and the minimum focus shift occurs at $\rho = 0$. The maximum focus shift caused by Z_{16}, Z_{21}, Z_{22} occurs at $\rho = 0$, and the minimum focus shift occurs near $\rho = 0.7$–0.8. The diffraction spectrum of the measurement mark should have its orders positioned in the regions of the entrance pupil where large phase errors are introduced by even aberrations, and consequently the sensitivity to focus shifts is large.

From Eq. (6), it can be seen that the spectrum distribution of the alternating phase-shifting grating that is used as measurement mark depends on the line/space ratio, 1:m. Using the lithographic simulator PROLITH, the line/space ratio of the alternating phase-shifting gratings is optimized to obtain the maximum sensitivity to spherical aberration and astigmatism. In our PROLITH simulation, the aerial image of the measurement mark is simulated, and no photoresist is used. In our simulation, the NA is 0.5–0.8, and the partial coherence is 0.3–0.8. The linewidth of the alternating phase-shifting grating used in the simulation is 250nm, which is