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Polarization effects induced by the bi-layer attenuated phase-shift mask and their impacts on near-field distribution

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ABSTRACT

As ArF projection lithography is approaching 45 nm technology node and beyond, polarization effects induced by mask are remarkable. At this mask dimension, traditional Kirchhoff approximation is invalid. Rigorous mask model is needed for accurate evaluation of mask diffraction. In previous works, many researchers are focus on the single grating layer diffraction. In this paper, Lee's formulation based on rigorous coupled wave analysis is applied to simulate the bi-layer grating diffraction in lithography. Then, polarization states as function of mask and incident light properties are evaluated. At last, the impacts on near-field distribution with different polarization state are further investigated. The image quality becomes worse under TE polarization, when Ta thickness becomes 35 nm, where the phase effects are effectively reduced. There should be a tradeoff between them.

1. Introduction

At 45 nm technology node and beyond, the mask feature ranges around the order of magnitude for the ArF wavelength. This mask dimension, high NA optical system and the use of immersion lithography cause the polarization effects induced by mask to be very remarkable [1–3]. The Kirchhoff approach, in which the diffracted light is computed by the scalar diffraction theory, is invalid. Rigorous electromagnetic field (EMF) models are needed to simulate the light diffracted from the photomask. Rigorous EMF modeling computes the numerical solution of Maxwell equations with electromagnetic boundary conditions to obtain the mask diffraction fields. Various numerical approaches, such as finite-difference time domain method (FDTD), rigorous coupled wave analysis (RCWA), the waveguide method (WGM), or finite element methods (FEMs), are adopted to solve Maxwell equations for the mask diffraction problem [2]. In this paper, RCWA was used to study the polarization effects induced by mask.

The RCWA has matured and become one of the most popular methods for grating diffraction simulation. The precision of the solution depends merely on the number of truncated orders in the electromagnetic field expansion [4–7]. In 1995, Moharam et al. presented a stable and efficient numerical implementation the rigorous coupled-wave analysis of binary gratings. However, they are used to model single layer grating diffraction and the convergences are bad for TM polarization [8]. In 2004, Wook Lee provided an extended version of the (2×2) matrix method for the grating-embedded multilayer structure diffraction. The performance of convergence is better for TM. But there only is one embedded grating layer is analyzed [9]. In this paper, the mathematical model in Ref. [9] is applied to simulate the two grating layers' diffraction in projection lithography. And the propagation matrices and dynamic matrices of the two grating layers are computed.

Our work is focused on the discussion of polarization effects induced by bi-layer attenuated phase shift mask (Att.PSM), and their impacts on near-field distribution. The mask model based on RCWA is presented in Section 2. In Section 3, we verify our code's correctness and discuss some typical results of a mask diffraction analysis. At last, the polarization effects on near-field distribution are simply investigated with the three-beam interference theory [10]. Some valuable conclusions will be outlined in Section 4.

2. The mathematical models

Firstly, the mask model is introduced. The Att.PSM diffraction problem is depicted in Fig. 1. The mask consists of two stacks on the substrate. The relative permittivity and the thickness of 1st layer, which is located in the region of $z_0 < z < z_1$, are $\varepsilon_1(x)$ and d_1, respectively. f_1 is the duty cycle defined as the fraction of the mask period (Λ_1) occupied by the length of absorber along the x axis. The period and duty cycle in the 2nd mask grating layer are the same as the ones in the 1st layer. The permittivity distributions and their

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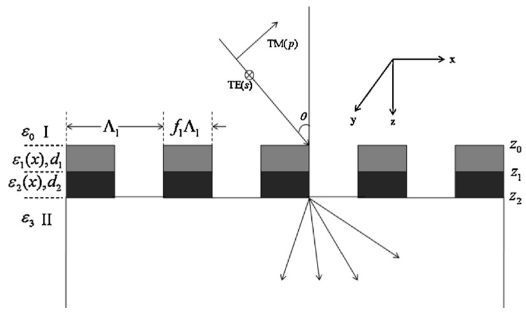

Fig. 1. Setup for Att.PSM diffraction problem. The sketched case presents the planar diffraction.

inverses in the two grating layers can be expanded in a Fourier series as

$$\varepsilon_\ell(x)=\sum_h \varepsilon_{\ell,h}\exp\left(\frac{i2\pi hx}{\Lambda_\ell}\right);\quad (\ell=1,2) \tag{1}$$

$$\frac{1}{\varepsilon_\ell(x)}=\sum_h \bar{\varepsilon}_{\ell,h}\exp\left(\frac{i2\pi hx}{\Lambda_\ell}\right);\quad (\ell=1,2) \tag{2}$$

in which $\varepsilon_{\ell,h}$ and $\bar{\varepsilon}_{\ell,h}$ denote the hth Fourier harmonic in the ℓth layer. The top ($\ell=0$) and bottom ($\ell=3$) layer are the incident and output regions, which are infinite in the $-z$ and z direction, respectively.

Suppose that the plane wave of a unit amplitude is incident on the top layer at a polar angle θ. The normalized solutions in the incident ($z<z_0$, $\ell=0$) and output ($z<z_2$, $\ell=3$) regions and in the ℓth layer ($z_{\ell-1}<z<z_\ell$, $\ell=1,2$) can be expressed, respectively, as

$$U_0(x,z)=\sum_m\{\delta_{m0}\exp[-ik_oq_{0,m}(z-z_0)]+B_{0,m}\exp[ik_oq_{0,m}(z-z_0)]\}\times\exp(-ik_{xm}x) \tag{3}$$

$$U_3(x,z)=\sum_m A_{3,m}\exp[-ik_oq_{3,m}(z-z_2)]\times\exp(-ik_{xm}x) \tag{4}$$

$$U_\ell(x,z)=\sum_m\sum_j w_{\ell,mj}\{A_{\ell,j}\exp[-ik_oq_{\ell,j}(z-z_\ell)]+B_{\ell,j}\exp[ik_oq_{\ell,j}(z-z_\ell)]\}\times\exp(-ik_{xm}x)\quad(\ell=1,2) \tag{5}$$

where δ_{m0} is the Kronecker delta function, and k_0 is the wavenumber in the free space. For TE and TM polarizations, the fields in Eqs. (3)–(5) indicate the electric- and the magnetic-field, respectively, which are normal to the incident plane. $w_{\ell,mj}$ and $q_{\ell,j}$ are the elements of the eigenvector matrix and the positive square root of the eigenvalues of the characteristic matrix for both polarization. All other detail parameters please refer to Ref. [9].

Due to the two gratings in the investigated mask, the propagation matrix $\mathbf{P}_\ell$ and the dynamic matrix $\mathbf{D}_\ell$ for each grating layer should be computed according to Eqs. (7)–(11) in Ref. [9]. And by the enhanced transmittance matrix method, the transmitted orders' amplitudes can be obtained. Then, the diffraction efficiencies are given by

$$\eta_3(m)=\begin{cases}|A_{3,m}|^2\times Re\left(\dfrac{q_{3,m}}{q_{0,0}}\right) & \text{for } TE\\[2ex] |A_{3,m}|^2\times Re\left(\dfrac{n_0^2q_{3,m}}{n_3^2q_{0,0}}\right) & \text{for } TM\end{cases} \tag{6}$$

Besides the diffraction efficiency, the polarization of a mask can be characterized by the degree of polarization (DoP)

$$DoP_m=\frac{\eta_m^{TE}-\eta_m^{TM}}{\eta_m^{TE}+\eta_m^{TM}}\times 100\% \tag{7}$$

where the upper index of η represents TE- and TM-polarization, respectively. DoP is positive when the photomask acts as the TE polarizer and negative for the TM polarizer.

After evaluating mask diffraction, the polarization effects on near-field distribution are simply investigated with the three-beam interference. The intensity in the image plane can be obtained with an interference of the zero order, the positive- and negative-first diffraction orders [10]. The intensity for TM polarization is expressed as

$$\begin{aligned}I&=(a_0+a_{+1}+a_{-1})(a_0+a_{+1}+a_{-1})^*\\&=e_0+2e_1+4\sqrt{e_0e_1}\cos(k_xx)\cos(\Delta\phi)\cos\theta\\&\quad+2e_1\cos(2k_xx)\cos(2\theta)\end{aligned} \tag{8}$$

where e_0 and e_1 are the diffraction efficiencies of the zero and positive-first orders, respectively. $\triangle\phi$ indicates the phase difference between zero and first diffraction orders. θ represents the diffraction angle for the 1st order. The intensity for TE polarization is given in Eq. (2) in Ref. [10]. All other detailed parameters please refer to Ref. [10].

3. Numerical results

By our mask model, the changes of polarization state as function of mask and incident light properties are simulated. We consider the bi-layer Att.PSM shown in Table 1 [2]. If it is not pointed out clearly, the default Critical Dimension (CD) of dense line/space pattern is 45 nm (wafer scale). And the light (TE or TM polarization) is normally incident on the mask top.

3.1. Verification of our model correctness

Firstly, in order to verify our code's correctness, the convergences of the diffraction efficiencies of the first orders for TE- and TM-polarization are computed. Our numerical result is shown in Fig. 2, which matches well with the result in Fig. 6 in Ref. [9]. In the following part, diffraction efficiencies and degree of polarization as a function of the mask and illumination properties will be investigated.

Table 1
Optical parameters of bi-layer Att. PSM investigated in this work. Ta is close to the substrate.

		n	k	Thickness (nm)
Att.PSM	Ta	1.63	2.58	21
	SiO_2	1.63	0.006	144

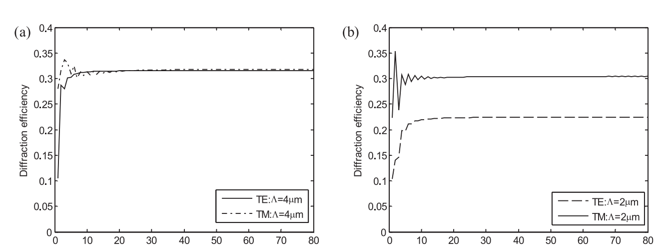

Fig. 2. The convergences of 1st order diffraction efficiencies versus the number of retained orders for (a) $\Lambda=4\,\mu$m and (b) $\Lambda=2\,\mu$m. The gap thickness is 1.6 μm. The other parameters are the same as used in Figs. 3 and 4 in Ref. [9].