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Single-mode-resonance interference in photoresist sub-micron waveguide for high exposure depth nanolithography

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ABSTRACT

A high exposure depth nanolithography technology is presented. In the proposed scheme, the photoresist layer is used as a waveguide. With a subwavelength grating (SWG) coupling structure, the incident light is efficiently coupled into the photoresist waveguide, in which the single-mode-resonance (SMR) interference field is formed. Different from other interference lithography, the new scheme can realize high resolution and high exposure depth simultaneously. In this paper, the theoretical model of the SMR interference is established to analyze the light field distribution in the photoresist. The simulation result shows that interference pattern with period smaller than 140 nm and depth larger than 900 nm can be obtained in the photoresist, by using 441 nm incident light and 276 nm period grating coupling structure.

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1. Introduction

Nano-gratings have many potential applications, such as far-field superlens (FSL) [1], polarizing beam splitter [2] and optical switch [3]. In the field of nano-grating fabrication, researchers are trying to obtain nano-grating with both small period and high aspect ratio, which demand for the lithography with high resolution and high exposure depth simultaneously. Deep-UV (DUV) and Extreme-UV (EUV) projection lithography use short illumination wavelength and high numerical aperture projection lens to achieve high resolution [4,5]. However, the exposure depth is restricted by the depth of focus of projection lens [6], which means that a higher resolution corresponds to a smaller exposure depth. As an alternative, various near-field lithography techniques, based on the interference of the evanescent electromagnetic wave [7–10] or surface plasmon polariton [11–18] have been presented. Nevertheless, the interference field intensity decays rapidly with the increase of propagation distance, which means that their exposure depths are still restricted in principle. In conclusion, the resolution and exposure depth of the existing optical lithography technology are mutually constrained, which makes it difficult to realize nanostructure fabrication with high aspect ratio.

In order to break through the constraint between resolution and exposure depth, the single-mode-resonance interference lithography (SMRIL) is proposed. A subwavelength grating (SWG) coupling structure is employed to excite diffraction orders with the transverse wave vectors much larger than that in free space. Photoresist layer plays the role of waveguide in the SMRIL configuration. Under SMR condition, only the ±1st diffraction orders excited by the SWG are coupled into the photoresist to excite single guided-mode. The interference field will be generated by the two oppositely propagating single guided-modes. Due to the large transverse wave vectors excited by SWG, the period of the interference pattern is smaller than λ/3, which means that the SMRIL has high resolution. In addition, the interference pattern produced by the two counter-propagating single guided-modes is much deeper than that in evanescent electromagnetic wave interference lithography (EEWIL) and surface plasmon polariton interference lithography (SPPIL), which indicates that the SMRIL has high exposure depth. What's more, the SWG coupling structure can be used as a lithography mask and is easy to be fabricated by the conventional interference lithography. That means that the SWG is reusable which leads to a low cost and high efficiency.

2. Theoretical analysis

Fig. 1(a) shows the schematic of the SMRIL which consists of two parts. One is the SWG which is composed of glass ($n = 1.47$), periodic ridge (polystyrene, $n = 1.59$) and match layer (PMMA, $n = 1.49$). The other part is the photoresist (AR 3170, $n = 1.61$) with thickness of h coated on the substrate ($n = 1.51$). The match layer of PMMA with $H = 500$ nm does not only provide the matching refractive index but

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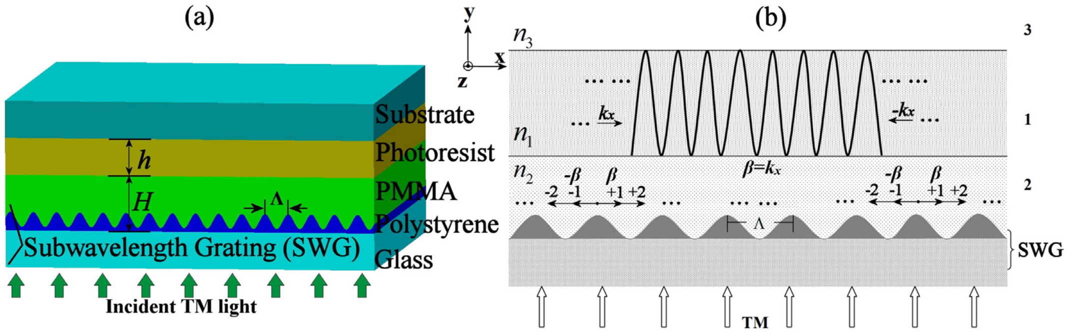

Fig. 1. (a) Schematic of SMRIL. (b) Illustration of theoretical analysis.

also protect the SWG, which makes the SWG a reusable lithography mask.

Fig. 1(b) shows the illustration of theoretical analysis. Regions 1, 2 and 3 compose the dielectric waveguide supporting multiple guided-modes. Region 2 is combined with SWG, which is able to excite different diffraction orders. Under SMR condition, only the ±1st diffraction orders can be coupled into photoresist, which transform into two oppositely propagating single guided-modes in the photoresist waveguide and result in the interference pattern.

In order to realize interference lithography with single-mode-resonance (SMR), the wave vector matching condition and single standing wave condition should be valid simultaneously. Then the SMR condition can be defined under the circumstance. Through the derivation of SMR condition, the theoretical model of SMRIL can be established, which is shown in the following.

2.1. Wave vector matching condition

This condition can be obtained by discussing the dispersion function in SWG and the dielectric waveguide.

For SWG diffraction, the dispersion function is (only +1st diffraction order is considered for convenience):

$$k_0 \sin(\varphi) + \frac{2\pi}{\Lambda} = \beta$$

where $k_0 = 2\pi/\lambda$. φ is the angle between k_0 and y axis, and β is the x direction wave vector of +1st diffraction order.

For perpendicular incident light ($\varphi = 0$), the dispersion relationship can be simplified to:

$$\beta = \frac{2\pi}{\Lambda}. \tag{1}$$

The relationships of wave vectors in 1, 2 and 3 regions are as follows:

$$k_x{}^2 + k_{1y}{}^2 = k_1{}^2 = k_0{}^2 n_1{}^2 \tag{2}$$

$$k_x{}^2 - k_{2y}{}^2 = k_2{}^2 = k_0{}^2 n_2{}^2 \tag{3}$$

$$k_x{}^2 - k_{3y}{}^2 = k_3{}^2 = k_0{}^2 n_3{}^2 \tag{4}$$

where n_2 is the effective refractive index [19] of region 2 which is related to the matching layer of PMMA and the ridge profile of SWG. And the sinusoidal grating is used as the coupling structure in this paper for practical, because most of the SWG fabricated by interference lithography have a sinusoidal ridge profile. n_3 is the refractive index of substrate, and n_1 should be larger than both n_1 and n_2 to form a dielectric waveguide. k_x is the x direction wave vector of the dielectric waveguide. k_{1y}, ik_{2y} and ik_{3y} are the y direction wave vectors in regions 1, 2 and 3 respectively.

Hence the dispersion function of the TM mode in photoresist waveguide is:

$$\tan(k_{1y}h - m\pi) = \frac{n_1{}^2 k_{1y}\left(n_3{}^2 k_{2y} + n_2{}^2 k_{3y}\right)}{n_2{}^2 n_3{}^2 k_{1y}{}^2 - n_1{}^4 k_{2y} k_{3y}}. \tag{5}$$

From Eqs. (2) to (5), k_x of different mode number m in the waveguide can be obtained. When k_x is equal to β, the wave vector matching condition is satisfied, that is:

$$k_x = \beta. \tag{6}$$

2.2. Single standing wave condition

The interference field distribution in the photoresist is decided by k_x and k_{1y}. k_x is the x direction wave vector in the photoresist with two oppositely propagating directions which leads to the interference pattern. k_{1y} leads to the standing wave in y direction. From Eqs. (2) to (5), k_x and k_{1y} can be written as:

$$k_x = k_x(\lambda, h)$$

$$k_{1y} = k_{1y}(\lambda, h).$$

Under wave vector matching condition for a given λ, the interference pattern period T and adjacent wave nodes distance L can be expressed as:

$$T = \pi/k_x = \Lambda/2 \tag{7}$$

$$L = \pi/k_{1y} = L(h, \Lambda). \tag{8}$$

To realize lithography with a uniform interference pattern, the single standing wave condition should be satisfied with h being smaller than L, which can be expressed by the mode number m:

$$\begin{cases} m = 0, & \left(n_2{}^2 n_3{}^2 k_{1y}{}^2 - n_1{}^4 k_{2y} k_{3y}\right) > 0 \\ m = 1, & \left(n_2{}^2 n_3{}^2 k_{1y}{}^2 - n_1{}^4 k_{2y} k_{3y}\right) < 0 \end{cases} \tag{9}$$

Then h can be determined:

$$h = \left[\arctan\left(\frac{n_1{}^2 k_{1y}\left(n_3{}^2 k_{2y} + n_2{}^2 k_{3y}\right)}{n_2{}^2 n_3{}^2 k_{1y}{}^2 - n_1{}^4 k_{2y} k_{3y}}\right) + m\pi\right] / k_{1y}. \tag{10}$$

2.3. SMR condition

When the wave vector matching condition Eq. (6) and single standing wave condition Eq. (9) are both valid, the SMR condition is established.

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