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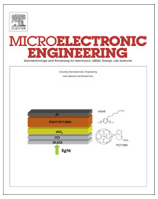

Solid immersion interference lithography with conformable phase mask

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ABSTRACT

This study proposes a simple and cost-effective method of solid immersion interference lithography that uses a conformable phase mask. Perfluoropolyether based polymer was used as the material of the elastomeric phase mask. The proposed method requires no liquid layer to function as the coupling medium or the index matching layer and keeps the photoresist free from the contamination of liquid. The solid coupling medium improves the resolution of interference fringes by a factor of its refractive index. This study presents an exposed interference fringe with a half-pitch of 58 nm using a He-Cd laser with $\lambda = 325$ nm, which corresponds to a feature size of $\lambda/5.6$.

1. Introduction

Periodic structures have received great attention for their numerous applications, such as photonic crystals [1], metamaterials [2], plasmonic nanostructures [3,4], wire grid polarizers [5,6], antireflective nanostructures [7], microlenses arrays [8], microsieves [9], magnetic data storage [10], micro/nano-fluidic devices [11,12], and biomaterials [13,14]. Interference lithography (IL) is based on the exposure of interference fringes produced by coherent beams, and provides a simple and high-throughput way to print high-resolution periodic features over a large area. The following equation expresses the pitch of the fringe pattern for two-beam interference [15]:

$$\Lambda_{fringe} = \frac{\lambda}{2n_{coupling}\sin\theta} \tag{1}$$

where λ is the exposure wavelength, $n_{coupling}$ is the refractive index of the coupling medium, and θ is half of the angle between the propagation directions of the two beams.

New applications continue to drive the demand for smaller nanostructures. For example, photonics devices that operate in the visible wavelength regime require subwavelength structures. Examples include photonic crystals, metamaterials, wire grid polarizers, and antireflective nanostructures. High volume magnetic data storage devices require a high density magnetic island array. Eq. (1) shows that the pitch of the interference fringe created by IL can be further reduced using a light source with a shorter wavelength [16–18] or adopting a coupling medium with a higher refractive index [19–23]. Furthermore, even higher resolution can be obtained with the utilization of evanescent waves [24–27].

Previous methods [19–21,24–26] require a liquid layer to function as the coupling medium or the index matching layer. However, the presence of air bubbles in this liquid layer may negatively affect the resist image formation [19,28]. This liquid layer must be uniformly distributed and its refractive index must be consistent. The material released from the resist may contaminate the surface of the optical component and resist, degrading the pattern quality [19]. This study proposes a simple and cost-effective patterning method of solid immersion interference lithography. The proposed approach requires no liquid layer.

2. Materials and methods

2.1. Solid immersion lithography with conformable phase mask

Fig. 1(a) presents a schematic configuration of the solid immersion lithography with a conformable phase mask. A glass substrate coated with the SU-8 (MicroChem Corp.) resist was placed upside down to serve as the solid coupling medium. An elastomeric phase mask was placed on the glass substrate. The use of an elastomeric mask allows close contact between the glass substrate and the phase mask. Therefore, it is not necessary to insert an index matching liquid between the substrate and mask. To further ensure close

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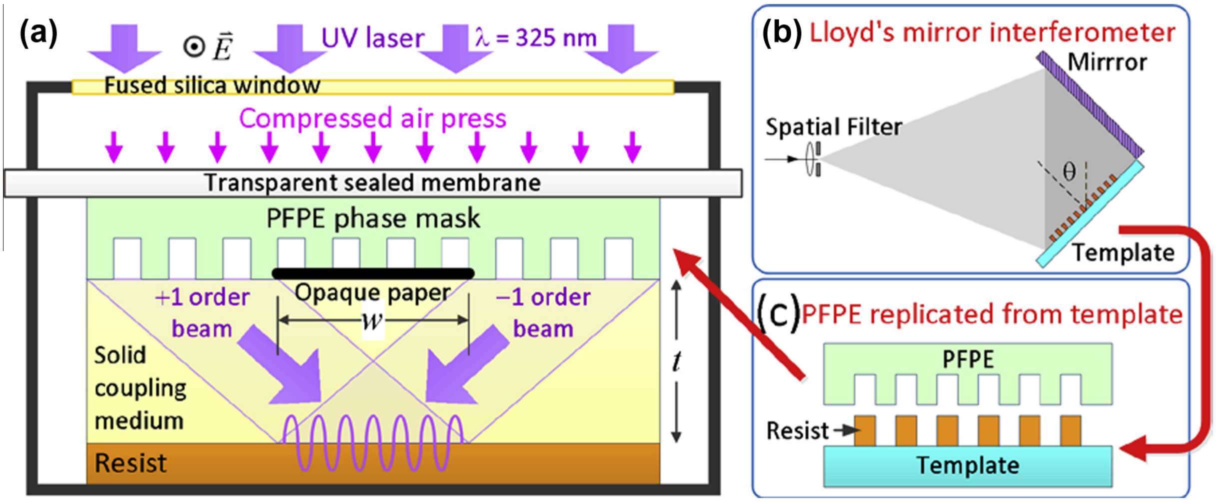

Fig. 1. (a) The schematic configuration of the solid immersion lithography with a conformable phase mask. (b) Master template was fabricated using Lloyd's mirror interferometer. (c) PFPE phase mask was replicated from master template.

contact between the mask and the substrate, the mask and the substrate were sealed in a chamber with a fused silica window on top. A transparent elastomeric membrane covered the phase mask to seal the mask/substrate system. A compressed air press (CAP) [6] was applied on the membrane with a small pressure less than 1 bar. The elastomeric membrane equilibrates the pressure from the CAP and then transfers the uniform pressure over the mask and substrate, resulting in good pattern uniformity during subsequent exposure. The laser beam from a He-Cd laser with $\lambda = 325$ nm passed through the fused silica window. The wave polarization was aligned with the grating direction of the phase mask to produce the best contrast in the interference fringe.

2.2. Elastomeric phase mask

Perfluoropolyether (PFPE, Fluorolink MD 700, Solvay Solexis) based polymers [29,30] were chosen as the phase mask materials. Compared with the more commonly used polydimethylsiloxane (PDMS, Sylgard 184, Dow Corning Corp.), PFPE's higher modulus avoids the collapse, merging, and buckling of the structures for small linewidths with higher aspect ratios. The extremely low surface energy ($\gamma = 12$ mN/m) [30] of PFPE facilitates an easier release from a master template made from the polymer nanostructures mentioned below. In fabricating the phase mask, a mixture of PFPE and photoinitiator (2,2-Dimethoxy-2-phenylacetophenone, Sigma–Aldrich, 1 wt.%) was poured on the master template. The sample was placed in a nitrogen environment and cured under UV light ($\lambda = 365$ nm) irradiation. After the curing process, PFPE can be much easier to be released from a polymer master template as compared to PDMS. The master template was a SU-8 periodic structure on a rigid substrate. The periodic patterns were created using Lloyd's mirror configuration [5,21] as illustrated in Fig. 1(b). Again, a He-Cd laser with $\lambda = 325$ nm was used as the light source. The nanostructures on the SU-8 template were further transferred to the PFPE as shown in Fig. 1(c). Both of the SU-8 templates and the PFPE phase masks can be repeatedly used.

2.3. Zeroth order beam blocking

Two-beam and multiple-beam interferences [16] can be achieved in the current proposed approach. The phase mask in this design functions as a beam splitter. The 0th order diffraction beam of a phase mask with a subwavelength pitch cannot be eliminated. Therefore, a sheet of opaque paper was inserted between the phase mask and the solid coupling medium to block this 0th order beam. The maximum width of the opaque paper, which can be derived from the geometric configuration illustrated in Fig. 1(a), depends on the thickness of the solid coupling medium by:

$$w_{\max} = t\frac{\lambda}{\sqrt{(n_{coupling}\Lambda_{pm})^2 - \lambda^2}} \tag{2}$$

where w_{max} is the width of the opaque paper, t is the thickness of the solid immersion medium, and Λ_{pm} is the pitch of the phase mask. From Fig. 1(a) and Eq. (2), the maximum patterning area depends on the width and pitch of the phase grating, the width of the opaque paper, the thickness and refractive index of the solid immersion medium, and the exposure wavelength. In this letter, the case of two-beam interference is utilized to demonstrate the proposed concept. A glass substrate was employed as the immersion medium and its thickness was 1.1 mm. The widths of the opaque paper were approximately 1.8 mm and 2.8 mm for the phase mask pitch of 252 nm and 232 nm, respectively.

Because of the 0th order beam blocking, the interference region under the opaque paper consisted of ±1st order diffraction beams only. The diffraction angle of the ±1st order beams [15] and the pitch of the interference fringe can be expressed as the following equations:

$$\sin\theta_{1\text{st}} = \frac{\lambda}{n_{coupling}\Lambda_{pm}} \tag{3}$$

$$\Lambda_{fringe} = \frac{\lambda}{2n_{coupling}\sin\theta_{1\text{st}}} = \frac{\Lambda_{pm}}{2} \tag{4}$$

where $\theta_{1\text{st}}$ is the incident angle of the ±1st order beams. When $\theta_{1\text{st}}$ approaches 90°, the ultimate resolution of the interference fringe exposed in the photoresist is:

$$\Lambda_{\min} = \frac{\lambda}{2n_{coupling}} \tag{5}$$

If $n_{coupling}$ is larger than n_{resist} (refractive index of photoresist) and the incident angle from the coupling medium to the photoresist exceeds the critical angle, the interference scheme moves into the regime of evanescent IL [24–27]. Because the evanescent wave decays exponentially, the exposure depth is limited and the image contrast is low. Several techniques, such as frustrated total internal reflection [24] and waveguide [25]/plasmon [26,27] assisted cou-