Fabrication and Alignment of Hybrid Gratings

Jingwen Li[1], Shengtong Wang[2] and Xinghui Li[1,2,#]
1 Tsinghua-Berkeley Shenzhen Institute, Tsinghua University, Shenzhen, 518055, China
2 Shenzhen International Graduate School, Tsinghua University, Shenzhen 518055, China
Corresponding Author / Email: ili.xinghui@sz.tsinghua.edu.cn

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As device complexity grows, multiple patterning techniques are used in the fabrication of combination pattern. Holographic lithography provides a cost-effective solution for periodic nanometers-level structures with high efficiency and scalability, while mask lithography is commonly employed for non-periodic structures with microns-level linewidth. Achieving precise alignment between these two regions is a significant technical challenge, as any misalignment can impact the overall device performance. To address this, advanced alignment techniques and optimized lithographic processes are required to ensure that the different patterns are properly coordinated, minimizing errors and enhancing the reliability and functionality of the final device.

In this paper, we present a novel fabrication process for hybrid gratings that integrates holographic lithography and masked lithography within a unified optical path. This process incorporates advanced alignment techniques to ensure accurate positioning of the two distinct patterned regions. The alignment signal is generated from the diffraction of a reference grating, which is integrated into the mask used for fabricating the codes. This reference grating, placed within the interference optical path, produces reference fringes recorded by a CCD camera. By analyzing and precisely adjusting these reference fringes, the alignment between the grating and encoding regions is optimized, thereby significantly increasing the performance.

1. Introduction

In micro- and nanofabrication, the demand for cross-scale optical processing is increasing, driven by the rising complexity of device designs. This poses challenges for various optical patterning techniques in microdevice manufacturing[1, 2]. Combination patterns are typically produced through multiple exposures using mask lithography, making the fabrication of high-quality masks critical. Laser direct writing and electron beam lithography are the main methods for mask production, both relying on precision motion systems to scan photoresist point by point. Laser direct writing, using ultraviolet light, is limited in resolution by the diffraction limit[3, 4]. In contrast, electron beam lithography, with its shorter wavelength, enables nanometer-scale precision, making it ideal for high-accuracy micro- and nanostructure fabrication[5]. However, its drawbacks include slow processing speeds, high costs, and reduced efficiency in large-area patterning. Additionally, both methods generate patterns via scanning, making consistency across large areas difficult to maintain.

Holographic lithography offers a flexible, cost-effective solution for periodic pattern generation[6]. By utilizing the interference of two coherent beams, it produces periodic structures in a single step, allowing for the fabrication of consistent photoresist masks and efficient large-area microstructure generation[7, 8]. Combined with mask lithography, holographic lithography can produce a wider range of patterns. Its potential for cross-scale applications is significant, as precise control over the phase, period, and direction of the interference field enables diverse photoresist patterns. When integrated with other lithography techn iques, holographic lithography enhances alignment and coordination between different pattern regions, facilitating standardized devices and minimizing variability in mass production.

In this paper, a new process to fabricate the hybrid grating is p roposed. Hybrid grating is a kind of device with combination pa ttern, which consists of grating and codes. Mask lithography and interference lithography are used to fabricate the grating and co des, and the lines in both of the areas are aligned. A photoresis t mask sample is fabricated and the quality is test.

2. Principle

Figure 1 shows the structure of the hybrid grating. Area I is the codes area, with the linewidth of several microns. Area Ⅱ is a grating, with a period of 1 μm. These two areas are coplanar but spatially separated, ensuring that their respective functions do not interfere with each other.

the fabrication of the hybrid grating photoresist mask was completed using a unified optical path. The codes area was generated using mask lithography, while the grating area was fabricated through holographic lithography.

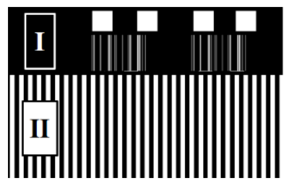

Figure 1 The structure of the hybrid grating

The principle of holographic lithography is shown in Figure 2. Two coherent plane waves are incident on the substrate at a angle of θ. The two coherent beams interfere with each other, forming interference fringes with a period of $g = \lambda / 2sin\theta$.

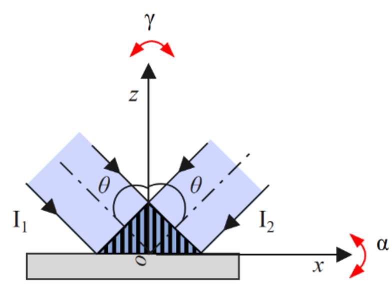

Figure 2. The principle of holographic lithography

To observe the orientation of the exposure field relative to the substrate, a reference grating G_{ref} is placed on the substrate S. The period of the reference grating, g_{ref}, is set to twice the interference period g of the two beams. According to the grating equation:

$$g_{ref}(\sin\alpha + \sin\theta) = m\lambda, m = 0, \pm1, \pm2, \cdots \quad (1)$$

In this equation, α is the diffraction angle generated by reference grating and m is the diffracted order. The +1st order diffracted light I_{ref1}, produced by beam I_1 passing through the reference grating, and the -1st order diffracted light I_{ref2}, produced by beam I_2 are emitted along the normal direction of the substrate. In practice, periodic errors ε occur during the fabrication of the reference grating, so the actual period is $g_{ref}=2g + \varepsilon$. This introduces a small angle between I_{ref1} and I_{ref2}, resulting in interference and the formation of observable macroscopic fringes. The period p of these fringes is given by:

$$p = \frac{g \cdot g_{ref}}{|\varepsilon|} \quad (2)$$

In the dual beam interference optical path, the direction of the grating lines in the fabricated grating depends on the polarization direction of the exposure beams. In Figure 3, the vibration direction of two exposure beams is $\mathbf{k}_1 = \mathbf{k}_2 = [0, 1, 0]^T$, which is the same as the direction of the interference fringe. The grating vector of the resulting grating is $\mathbf{g} = [1, 0, 0]^T$. When the grating vector of the reference grating aligns with the grating vector of the fabricated grating, the vibration direction of the reference diffracted light is consistent with that of the exposure beams. As a result, the direction of the reference fringes also aligns with both the reference grating and the fabricated grating, as shown in Figure 3(a).

When the substrate experiences roll relative to the exposure beams (i.e., rotation around the z-axis), the propagation and vibration directions of the reference diffracted light will change. On the CCD camera plane, the reference diffracted light will appear above and below the original spot position, as shown in Figure 3(b). Therefore, by adjusting the relative orientation between the exposure beams and the substrate attached with the reference grating, the direction of the fabricated grating lines can be controlled.

To fabricate the codes area and ensure alignment with the grating lines, a mask featuring a reference grating, as shown in Figure 4, was designed and produced. The mask is made of a quartz glass substrate, with a chromium film as the shading material. The pattern on the mask was generated using laser direct writing technology. The central portion of the mask is the grating area. The grating is produced through double exposure using two-beam interference. To prevent interference from the glass plate affecting the overall grating pattern, the grating area on the mask is left uncovered by glass. Reference gratings were fabricated at the corners of the codes area. Both the reference gratings and the lines in the absolute codes area were formed by scanning in the same direction.

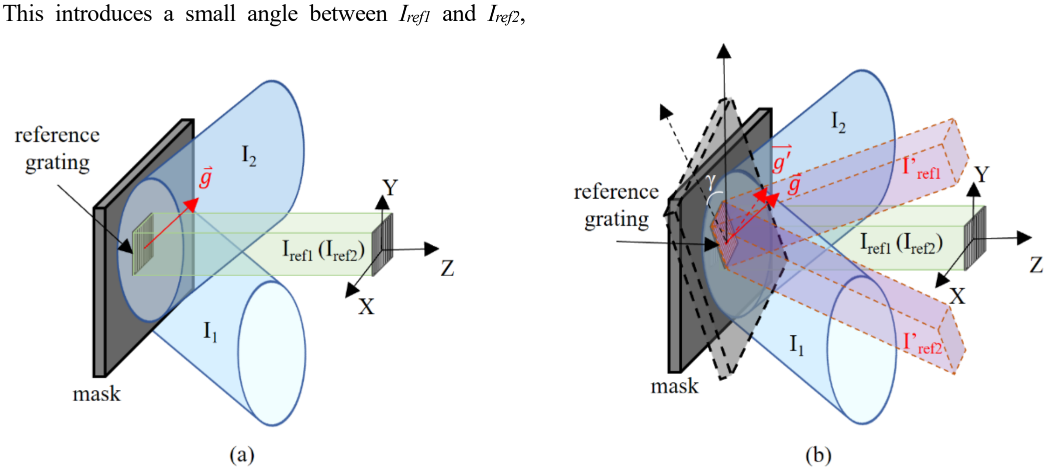

Figure 3 The principle of alignment

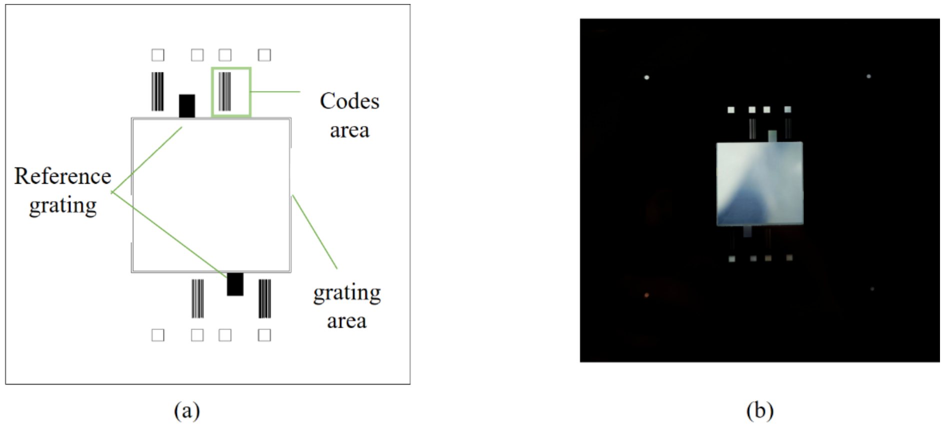

Figure 4 (a) Mask design diagram (b) Physical image of the mask

3. Fabrication and test

Before exposure, the reference fringes need to be adjusted to the correct position. The substrate with photoresist and the mask are mounted on a three-degree-of-freedom adjustment stage capable of pitch, yaw, and roll. Firstly, the mask is covered, leaving only the reference grating area exposed. The laser is turned on, and the two beams are directed onto the reference grating. The adjustment stage is fine-tuned to approximately align the two reference diffracted beams. A CCD camera is used to observe the reference fringes, and the posture of one of the beams is adjusted to make the fringes perpendicular to the optical table surface. Once the beam alignment is complete, the exposure process begins. After exposure, development and optical inspection are performed. The photoresist mask observed under the microscope is shown in the Figure 5. The lines in the encoding area are clear, and the alignment between the two regions is accurate.

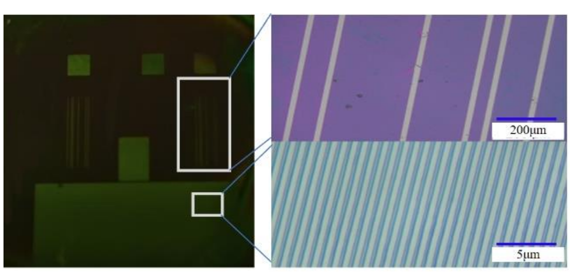

Figure 5 The fabricated hybrid grating

4. Conclusion

In the fabrication of combination devices, the alignment between functional regions plays a critical role in the device's performance. This paper proposes a method for fabricating the photoresist mask of the hybrid grating using a dual-beam exposure system. The principle of alignment is described and the process of aligning is introduced. The fabricated composite device mask shows good alignment performance.

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