Influence of fabrication parameters on groove profile of blazed gratings made with two-step holographic technique

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ABSTRACT

The two-step holographic technique of fabricating blazed gratings has been successfully applied to common positive photoresist. Influence of three fabrication parameters in the second step on groove profile of blazed gratings was studied experimentally. The three fabrication parameters are exposure, incident angle of laser beam and development time. The exposure distribution on the cross-section of one groove stripe of grating was modeled. Results of experiment and modeling with various exposures reveal that the technique is effective only when the symmetrical contour lines of exposure in the first step fade out with increasing second exposure. With other parameters fixed, experiments were also carried out with the beam incident angle varying from 10˚ to 80˚ and with the development time varying from 1 s to 9 s. Blazed gratings with quasi-triangular are obtained when incident angle reaches 40˚ and when development time reaches 5 s. Scanning electron micrographs of the results are presented. Blazed gratings with observed blaze angles of 20˚ to 50˚ were obtained by changing the incident angle. Efficiencies of different diffraction orders for gratings with various incident angles are also given.

Keywords: blazed grating, holographic, groove profile, fabrication parameters, two-step technique

1. INTRODUCTION

It is both strenuous and time-consuming to produce blazed gratings with the conventional ruling method. Holographic approach is a promising solution to produce blazed gratings with high speed and low cost. Among proposed holographic techniques1-11, the two-step technique10 is a feasible and simple one. The technique includes two holographic recording and development steps. In the first step, a grating with quasi-sinusoidal groove profile is fabricated on the recording material. In the second step, only one collimated laser beam irradiates on the recording plate with a selected incident angle, resulting in the change of groove profile into quasi-triangular after development. The technique was first applied to chalcogenide glassy semiconductor films10, which are often used as negative photoresist. To extend the applicability of the method, we have explored the possibility of applying the method to common positive photoresist and good results have been obtained in our previous work12. The final groove profile is

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influenced by several parameters: the groove profile formed in the first step, the beam incident angle and the exposure in the second step, the developer used and the development time in the second step, etc.

In the paper we present our study emphasized on the influence of fabrication parameters in the second step, including exposure, incident angle of the laser beam and development time, on the final groove profile of gratings, in order to obtain optimal fabrication parameters for required blazed gratings. Results of experiment and exposure distribution modeling with various exposures reveal that the two-step technique is effective only when the symmetrical contour lines of exposure in the first step fade out with increasing second exposure. With other parameters fixed, experiments were carried out with the beam incident angle varying from 10° to 80° and with the time of development varying from 1 s to 9 s. Blazed gratings with quasi-triangular are obtained when incident angle reaches 40° and when development time reaches 5 s. Scanning electron micrographs of the results are presented. Blazed gratings with observed blaze angles of 20° to 50° were obtained by changing the incident angle, efficiencies in different diffraction orders of which are also given.

2. FABRICATION PARAMETERS IN THE SECOND STEP

Although some results of numerical modeling for the second step of the two-step technique have been given\(^\text{10}\), which are mostly qualitative, the only practical solution is to empirically optimize fabrication parameters of the entire process, for there are so many fabrication parameters that influence the final groove profile of gratings. In our experiment, the recording material used was CHP-C positive photoresist. 458 nm laser light was used as the recording source and 1.38% sodium hydroxide solution as the developer. The following three parameters in the second step were studied experimentally in sequence: firstly the exposure, then the incident angle of the laser beam and lastly the development time. The parameters in the first step were the same for all experiments: the angle between the two identical symmetric collimated beams was 18°; the intensity for both beams was about 6.5 mW/cm\(^2\) and the exposure time was 15 s; the development time was about 6 s at room temperature.

2.1 The exposure

To our knowledge, the influence of the exposure in the second step of the two-step technique on final groove profile of gratings has not yet been studied. In our research, the influence was first studied experimentally with the incident angle and the development time fixed, which were 64.4° and about 6 s respectively. For convenience and easy comparison with the exposure in the first step, one of the two identical beams in the first step was used for the second exposure. The exposure time was increased twofold from 15 s. The intensity of laser beam was fixed, so the exposure was also increased twofold. Following an exposure, the plate was subjected to chemical processing in 1.38% sodium hydroxide solution for about 6 s, thoroughly rinsed in deionized water, and dried with a hot-air blower. Then groove profile of the grating was observed timely but indirectly through transmission efficiency measurement of different diffraction orders. The measured efficiency is relative efficiency defined as Ref. 12. The measurement was made by using a 633 nm laser beam at normal incidence on the gratings from the side of photoresist and the detector of a power meter to receive the transmitted light power in different diffraction orders. As a result, the gratings with the exposure time of 15 s and 30 s have an almost symmetrical energy distribution on two sides of the zeroth order and the highest efficiency at the zeroth order. The grating with the exposure time of 60 s also has an almost symmetrical energy distribution on two sides of
the zeroth order, but the efficiency of the zeroth order is nearly equal to those of the ±1st order. When the exposure time reaches 120 s, the grating begins to have a distinctly asymmetric energy distribution, i.e., the efficiency ratio between the –1st order and the +1st order begins to be obviously greater than 1. The –1st order has the highest efficiency and the zeroth order just has a half. With the exposure time increasing, the efficiency ratio between the –1st order and the +1st order and the efficiency of the –1st order reach their maximums at the exposure time of 240 s and both begin to decrease after that. Thus, we choose 240 s as the exposure time in the second step for following experiments in Subsection 2.2 and 2.3 though 240 s may not be the optimal value.

The results of experiments show that the two-step technique is effective, i.e. the grating has asymmetric groove profile, only when the exposure in the second step reaches certain value, and maybe there’s an optimal value for the second exposure when other parameters are fixed. In order to prove this, we make a theoretical analysis of the exposure distribution in photoresist after the second exposure. The exposure distribution on the cross-section of one groove stripe of the grating was modeled. For each point in the photoresist, the final exposure is the sum of the first exposure and the second exposure. The intensity of the first exposure can be expressed as

\[ I = 4I_1 \cos^2 \left( \frac{\delta}{2} \right), \]  

where \( I_1 \) is the intensity for both beams and \( \delta \) is the optical length difference between the two beams. If the vector of grating is along the coordinate axis of \( x \), the difference can be written as

\[ \delta = \frac{4\pi}{\lambda_0} x \sin \frac{\theta}{2}, \]  

where \( \lambda_0 \) is the wavelength of beams in air and \( \theta \) is the angle between the two beams. Then the exposure in the first step, which is the product of intensity and exposure time \( t \), can be expressed as

\[ E = 4I_1 t \cos^2 \left( \frac{2\pi}{\lambda_0} x \sin \frac{\theta}{2} \right). \]

Fig. 1. Comparison of the SEM image and the calculated groove shape for the edge of grating stripes

The second exposure distribution in photoresist depends on the intensity and incident angle of laser beam in the second step, the groove profile of gratings after the first step and the second exposure time. To determine groove profile of gratings after the first step, diffracted power in different orders was measured when the gratings were illuminated normally. The measured values are approximately equal to the theoretical ones calculated with the well-known result\(^4\) that the diffracted power in order \( n \) of a normally illuminated sinusoidal phase grating is given by \( J_n^2(x) \), where
$J_n(x)$ is the Bessel function of the first kind of order $n$ and $x$ is the variation amplitude of phase. Then we can make a conclusion that gratings after the first step have a sinusoidal groove profile and the amplitude calculated from the measured results is 0.28 microns. Fig. 1 shows comparison of the SEM image and the calculated groove shape for the edge of grating stripes, and the fit between them appears to be good.

![Fig. 2. Exposure distribution modeling for gratings with the fabrication parameters used in the above experiments](image)

(a) For gratings after the first step  
(b)-(g) For gratings with the second exposure time of 15 s, 30 s, 60 s, 120 s, 240 s and 480 s respectively

Modeling for gratings with the fabrication parameters used in the above experiments and the groove profile shown in Fig. 1 are represented by contour lines of exposure in Fig. 2. The unit is micron for coordinates and mJ/cm² for color bar on the right in all figures. Only one stripe of the grating is presented. Fig. 2(a) is for gratings after the first step and the other figures are for those with the second exposure time of 15 s, 30 s, 60 s, 120 s, 240 s and 480 s respectively. In Fig. 2(b)-(g), the symmetrical contour lines of exposure as those in Fig. 2(a) fade out with increasing second exposure time corresponding to the gradual disappear of the symmetrical energy distribution. The symmetrical contour lines of
exposure finally disappear when the time reaches 120 s. This is corresponding to the above experimental result that the grating has an almost symmetrical energy distribution before the time reaches 120 s and begins to have a distinctly asymmetric energy distribution when the time reaches 120 s. The modeling seems to fit the experimental results well. Maybe it can provide approximately the required value of the second exposure in our further experiments. It may be concluded that only when the symmetrical contour lines of exposure in the first step fade out with increasing second exposure, the grating can have a distinctly asymmetric energy distribution corresponding to asymmetric groove profile. As to finding the optimal value for the second exposure, it needs further experiments and theoretical analyses. We temporarily choose 240 s as the second exposure time in Subsection 2.2 and 2.3.

2.2 The incident angle

It is revealed in Subsection 2.1 that when the two-step technique of fabricating blazed grating is effective, i.e. when the grating has an asymmetric groove profile after the second step, the second exposure is higher than the first one in the total exposure. Thus, it is meaningful to study the influence of the incident angle of laser beam in the second exposure on the final groove profile. The influence was studied experimentally with the second exposure and development time fixed, which were 240 s and about 6 s respectively. For convenience, one of the two identical beams in the first step was used for the second exposure as in Subsection 2.1. In addition to the angle of 64.4°, which was used in Subsection 2.1, the angles of 10°, 30°, 40°, 50°, 60°, 70°, 75° and 80° were also used as the incident angle of laser beam. Following an exposure, the chemical processing of plates was the same as that in Subsection 2.1. Relative transmission efficiency of different diffraction orders was measured as Subsection 2.1 and the efficiency ratio between the –1st order and the +1st order was calculated. Groove profile of gratings was also observed directly by SEM.

Efficiencies in different diffraction orders of gratings with various incident angles are shown in Fig. 3. The abscissa is for diffraction order and the ordinate is for efficiency the unit of which is percent. All gratings have asymmetric energy distribution, but show various degrees of asymmetry. With the incident angle increasing, both the efficiency of the –1st order and the efficiency ratio between the –1st order and the +1st order are increasing. The efficiency reaches its
maximum at the angle of 64.4° and 70° while the efficiency ratio reaches only at the angle of 64.4°, then both begin to decrease. Fig. 4 shows SEM images of section for gratings with a variety of incident angles. Gratings with the incident angles of 10° and 30° have a quasi-trapezoidal groove profile, which can be used to explain the low efficiency of the –1st order and the low efficiency ratio between the –1st order and the +1st order shown in Fig. 3. Gratings with incident angles of 40° to 80° have a quasi-triangular groove profile, observed blaze angles of which are shown in Fig. 5. Blazed gratings with observed blaze angles of 20° to 50° were obtained by changing incident angle in the second step. Suppose substrate and photoresist of the plate have the same refractive index, when the grating is illuminated normally from the side of photoresist, the relation between the blaze wavelength and the blaze angle can be expressed by

$$\lambda_b = dn \sin \left[ \theta_b - \arcsin \left( \frac{\theta_b}{n} \right) \right],$$

where \( \lambda_b \) is blaze wavelength of the first order, \( d \) is the period of grating, \( n \) is the refractive index of substrate and photoresist and \( \theta_b \) is the blaze angle of grating. In our experiment, \( d \) is 1.464 microns and \( n \) is about 1.6, thus blaze wavelengths of the first order for gratings with incident angles of 40° to 80° can be calculated according to (4) and the calculated results are 854nm, 854nm, 479nm, 566nm, 603nm, 479nm and 312nm respectively.

Fig. 4. SEM images of section for gratings with a variety of incident angles
Blaze wavelengths of the first order for gratings with the incident angles of 64.4° and 70° are closer to the wavelength of the incident light, 633nm, than those of other gratings, so they have higher efficiency of the −1st order shown in Fig. 3. For the influence of incident angle in the second step of the two-step technique, we can make a conclusion that there is a certain range of effective incident angles when other parameters are fixed; a range of blaze angles can be obtained by changing the incident angle, and different incident angles may correspond to the same blaze angle.

![Blaze angle vs Incident angle graph](image)

Fig. 5. Observed blaze angles of gratings with incident angles of 40° to 80°

### 2.3 The development time

Finally, we study the influence of the development time in the second step on the final groove profile. In our research, the influence was studied experimentally with the incident angle of laser beam and the exposure time fixed, which were 64.4° and 240 s respectively. The development time varied from 1 s to 9 s. Chemical processing of plates and efficiency measurement were the same as those in Subsection 2.1 and 2.2. Groove profile of gratings was also observed by SEM and the results corresponding to 1 s to 7 s are show in Fig. 6.

![SEM images of section](image)

Fig. 6. SEM images of section for gratings with a variety of second development times
Gratings with the development time less than 5 s have an almost asymmetric trapezoidal groove profile. Gratings begin to have a quasi-triangular groove profile when the development time reaches 5 s and the grating with the time of 7 s has a triangular groove shape exactly. As to the second development time, we make the conclusion that with increasing second development time, the sinusoidal groove profile after the first step gradually becomes trapezoidal, quasi-triangular and triangular finally. Only when the development time reaches a certain value, gratings with quasi-triangular or triangular groove profile can be obtained.

3. CONCLUSIONS AND DISCUSSION

The two-step holographic technique of fabricating blazed gratings has been successfully applied to common positive photoresist. Influence of three fabrication parameters on groove profile, including exposure, incident angle of laser beam and development time in the second step, was studied experimentally in the paper. The exposure distribution on the cross-section of one groove stripe of grating was modeled.

Results of experiment and modeling with various exposures reveal that the technique is effective only when the symmetrical contour lines of exposure in the first step fade out with increasing second exposure. Quasi-triangular groove profile can be obtained only with a certain range of incident angles when other parameters are fixed. A range of blaze angles can be obtained by changing the incident angle and different incident angles may correspond to the same blaze angle. As the development time increasing, the sinusoidal groove profile after the first step gradually becomes trapezoidal, quasi-triangular and triangular finally.

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REFERENCES


