The University of Osaka
Institutional Knowledge Archive

Title	Interference Exposure Fabrication of Blazed Grating by Phase-shifting Mask
Author(s)	Ura, Shogo; Kintaka, Kenji; Awazu, Hideyuki et al.
Citation	電気材料技術雑誌. 2011, 20(2), p. 79-82
Version Type	VoR
URL	https://hdl.handle.net/11094/76882
rights	
Note	

The University of Osaka Institutional Knowledge Archive : OUKA

https://ir.library.osaka-u.ac.jp/

The University of Osaka

電気材料技術雑誌　第20巻第２号
J. Soc. Elect. Mat. Eng.　Vol.20,　No.2　２０１１

Interference Exposure Fabrication of Blazed Grating by Phase-shifting Mask

Shogo Ura[1], Kenji Kintaka[2], Hideyuki Awazu[1], Kenzo Nishio[1], Yasuhiro Awatsuji[1], Junji Nishii[3]

[1]*Department of Electronics, Kyoto Institute of Technology, Matsugasaki, Sakyo-ku, Kyoto 606-8585, Japan*
[2]*National Institute of Advanced Industrial Science and Technology, 1-8-31 Midorigaoka, Ikeda, Osaka 563-8577, Japan*
[3]*Research Institute for Electronic Science, Hokkaido University, Kita 21 Nishi 10, Kita-ku, Sapporo 001-0021, Japan*
Tel: +81-75-724-7424, Fax: +81-75-724-7424
E-mail: ura@kit.ac.jp

Abstract

A simple interference exposure method using a phase-shifting mask was discussed on the basis of Fourier synthesis for fabricating blazed gratings. A phase-shifting mask was designed with 244 nm exposure-light wavelength to launch multiple diffraction beams so that resultant interference pattern fit to required optical intensity profile. Fine surface-relief pattern on SiO_2 mask for 3 μm-period sawtooth optical-intensity profile was fabricated by electron-beam direct-writing lithography with 30 nm scanning step and relief height of 65 nm. Sawtooth-like intensity profile was demonstrated with theoretically predicted interference visibility. A UV photoresist was exposed through the fabricated phase-shifting mask and developed to form a blazed grating.

1. Introduction

A blazed grating having sawtooth cross-section is widely used because of its high diffraction efficiency. Several techniques are used for fabricating such a grating. A popular method is the electron-beam (EB) direct writing exposure of low-Γ EB resist with dose control.[1,2) Tilt dry etching with thin-stripe mask loaded on a substrate was also utilized.[3) However, they are not suitable for large area patterning because of its low yield or the special etching layout. Optical exposure of low-Γ photoresist is attractive from the viewpoint of high-yield patterning of large area. An exposure method using a gray-tone mask can produce arbitrary cross-sectional profile[4-6) but is not good for short grating period or small feature size. An optical interference or holographic exposure method is applicable to a short grating period comparable to the wavelength of an exposure wave, but the conventional two-beam interference generates only a sinusoidal optical-intensity profile. An exposure technique utilizing tilt interference fringes was reported for blazed grating[7,8) but suitable only to transparent substrate. If a large number of waves can be interfered with precise control of their complex amplitudes, nearly sawtooth profile can be made by Fourier synthesis. Mach-Zehnder-interferometer-like exposure systems were proposed and discussed more than 30 years ago[9,10), though careful optical arrangement and high stabilization were required in order to adjust the complex amplitudes of the interfered waves.

Recently, a much simpler interference exposure method using a kind of phase-shifting mask was proposed and demonstrated by the authors[11,12). Multiple waves were generated by the diffraction by the mask having a fine periodic relief pattern of deep sub-wavelength feature size. The method utilizes both positive and negative diffractions, and the multiple harmonic waves diffracted by the mask propagate with tilted angles in the air gap and overlap on the photoresist to form a required sawtooth intensity pattern based on Fourier synthesis. Although it is impossible to control the positive and negative diffractions independently, there is no problem as far as the blazed grating has a uniform period. In other words, this mask-interference method is useful only for uniform blazed gratings. On the other hand, a chirp grating provides a lens function and is much preferable in many applications. Then we investigated another layout enabling the generation of a sawtooth optical intensity profile with a chirp period[13,14).

In this paper, we report a fabrication of a blazed grating of a uniform period by using a phase-shifting mask and preliminary experimental results.

2. Phase shift for sawtooth optical intensity

A basic layout of the proposed interference exposure system porviding sawtooth optical intensity with a uniform period is depicted in Fig. 1. A phase-shifting mask of a grating period Λ along y-direction is set apart by a separation air gap z_0 from a photoresist layer coated on a substrate.

A plane wave from UV laser propagates downward along the normal (z direction) of the mask and is shifted in phase by a relief on the bottom face of the mask to be split to multiple space harmonic waves. The phase shift can be written as

$$\delta(y) = \sum_{s=0}^{\infty} \delta_s \sin(sKy + \Delta_s), \qquad (1)$$

where $K = 2\pi/\Lambda$, and s denotes the order of harmonics. Parameters δ_s and Δ_s are real. The electric field of the wave just after transmission of the phase shifting relief at $z = 0$ can be expressed by

$$E(y) = E_0 \exp\{-j\delta(y)\}. \qquad (2)$$

The optical intensity is constant along y-direction at $z = 0$. From the periodicity, $E(y)$ can also be expressed by

$$E(y) = \sum_{p=-\infty}^{\infty} c_p \exp(-jpKy), \qquad (3)$$

where p represents the order of harmonics. The optical intensity is given by

$$I(y,z) = \left| \sum_p c_p \exp\left\{-j\left(pKy + \sqrt{k^2 - (pK)^2}\, z\right)\right\} \right|^2, \qquad (4)$$

where k is the wave number in the air. We fit $I(y, z_{op})$ to a target pattern $A(y)$ by optimizing z_{op} and expansion coefficients c_p. For a sawtooth pattern, $A(y)$ must be

$$A(y) = I_0\left(1 + \frac{2m}{\Lambda} y\right) = \sum_{q=-\infty}^{\infty} I_q \exp(-jqKy); \quad |y| < \frac{\Lambda}{2}, \qquad (5)$$

where m represents interference visibility, I_0 is the 0th order coefficient, and other coefficients I_q are given by

$$I_q = j(-1)^{q+1} \frac{mI_0}{q\pi}; \qquad (q \neq 0). \qquad (6)$$

c_p are chosen so that Eq. (4) is equivalent to Eq. (5), then $\delta(y)$ is determined from Eqs. (2) and (3). When $\delta(y)$ is small, δ_s and Δ_s giving Eq. (5) at the middle of photoresist are expressed approximately by

$$\delta_s = \frac{m}{s\pi \sin\left\{\left(k - \sqrt{k^2 - s^2K^2}\right)z_0 + \left(n_r k - \sqrt{n_r^2 k^2 - s^2K^2}\right)t_r/2\right\}},$$

$$\Delta_s = (s+1)\pi, \qquad (7)$$

where n_r and t_r are the refractive index and the thickness of the photoresist, respectively.

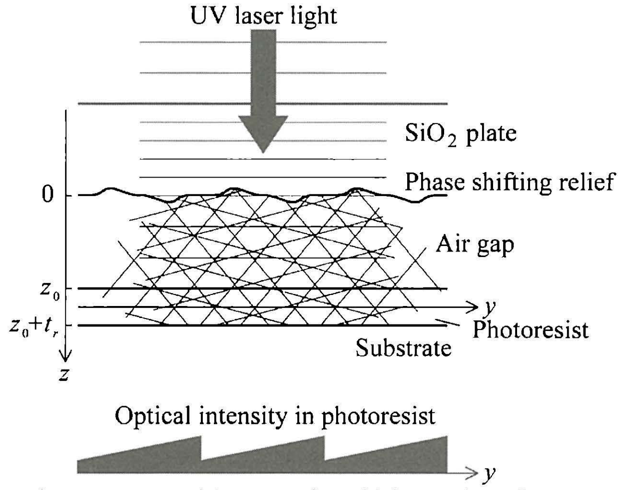
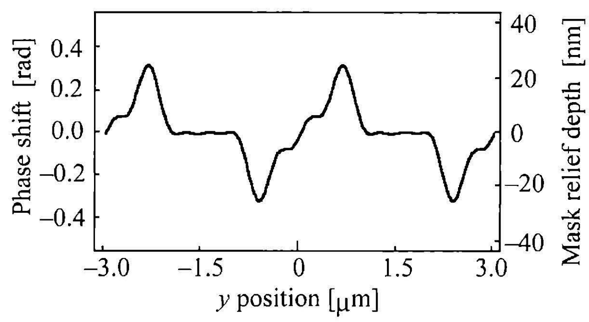


Fig. 1 Proposed layout of multi-beam interference exposure of blazed grating pattern with use of phase shifting mask.

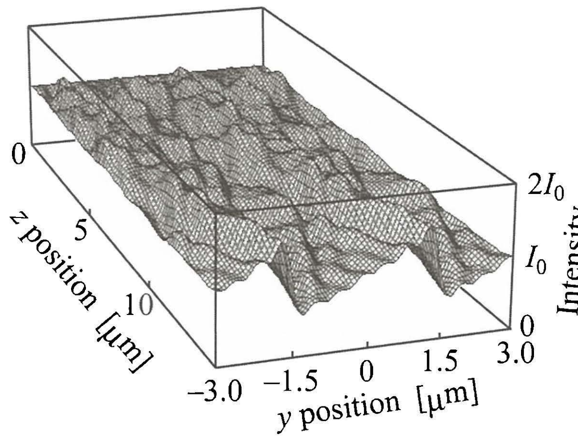
3. Design example of phase-shifting mask

A UV laser of 244 nm wavelength and SiO_2 glass of 1.51 refractive index were considered as exposure light source and mask material, respectively. t_r and n_r of UV resist are assumed to be 0.5 μm and 1.6, respectively. $\delta(y)$ was determined to give a sawtooth intensity profile in the middle of UV resist layer with m of 0.5.

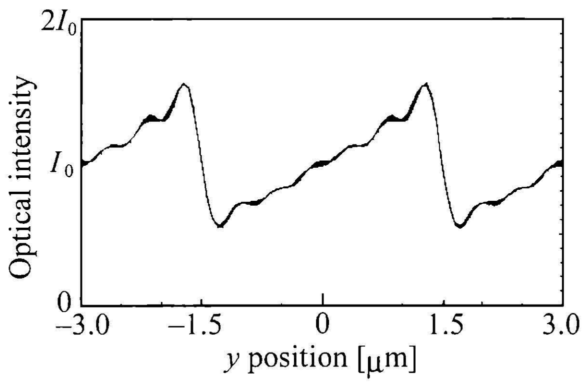
A design example is shown in Fig. 2 for 3 μm period grating. z_0 was chosen to be 14.6 μm. Harmonic waves up to 12th order can propagate in the air. A phase shift $\delta(y)$ was obtained by substituting Eq. (7) to Eq. (1) with the order s truncated at six, and is depicted in Fig. 2 (a). $\delta(y)$ can be directly converted to relief depth of a mask which is also shown on the right side axis. Calculated intensity distribution $I(y, z)$ from $z = 0$ down to $z = z_0 + t_r/2$ is shown in Fig. 2 (b). It can be seen that the sawtooth-like profile is gradually formed as propagation from the flat intensity distribution at $z = 0$. However, fine fluctuation is also seen in the resist at $z = z_0 + t_r/2$ because the interference occurs with limited harmonics. Intensity distribution shows no serious change along propagation in the resist ($z_0 < z < z_0 + t_r$) and is plotted in Fig. 2 (c).



(a) Phase shift distribution and mask relief



(b) Intensity distribution along propagation



(c) Intensity distribution in UV photoresist

Fig. 2 Design example of 3 μm period grating.

4. Fabrication and characterization of mask

The designed surface relief was fabricated by electron-beam (EB) direct writing lithography. Low-Γ EB resist and polythiophene (conductive polymer) were spin-coated on a SiO_2 glass substrate. EB was scanned along x-direction with step increment by 30nm along y-direction. Scanning speed of each line was controlled to give the dose distribution propotional to the required relief depth. After development, the relief pattern was measured by atomic force microscopy (AFM). A cross-sectional profile of the obtained relief is shown in Fig. 3. The pattern height from the bottom to the peak was 65 nm and fine structure similar to the designed one was obtained.

A plane wave of 244 nm wavelength was illuminated from the rear side of the substrate and the wave transmitted through the relief was collected by a UV objective lens and imaged on a UV image sensor. An example of the optical intensity distribution obtained with an air gap of 15 μm was shown in Fig. 4. A sawtooth-like intensity profile with theoretically predicted modulation depth was observed, although speckle noise caused by imaging optics degraded the shape. The obtained interference visibility was slightly larger than the designed one, which can be attributed to slightly deeper relief and higher refractive index of the EB resist. The relief pattern was transferred in the SiO_2 substrate by dry etching. The transferred relief height was about 60 nm. This height is equal to the designed one.

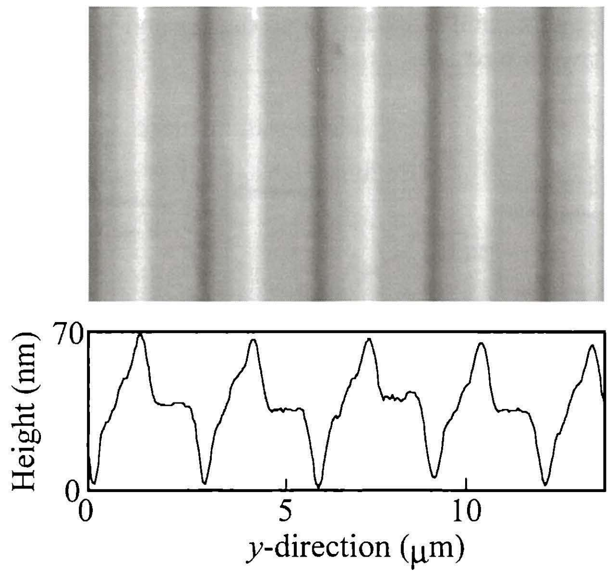


Fig. 3 AFM image and relief height of the fabricated mask.

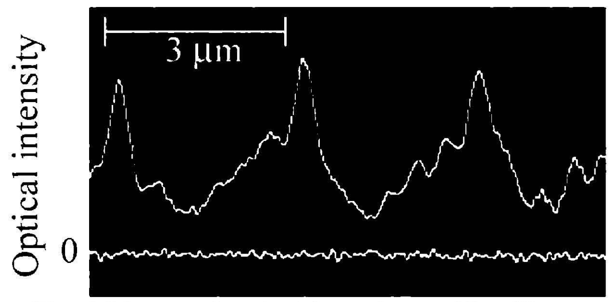


Fig. 4 Measured optical intensity profile. Shape degradation is due to noise by imaging optics.

5. Fabrication of blazed grating

A Pyrex glass is opaque for 244 nm wavelength and was chosen as a substrate in order to avoid multiple reflections inside the substrate which would degrade the interference pattern. A 0.5-μm-thick UV photoresist (M151Y provided by JSR) was coated on a 1-mm-thick Pyrex glass substrate. A layout for the exposure is illustrated in Fig. 5. The substrate was fixed to a stage with a 1μm- resolution encoder and set apart by 15 μm from the phase-shifting mask. Light from a UV laser (Ar+SHG) of 244 nm wavelength was spatially filtered, expanded, and collimated. Illumination power density was 15 $\mu W/cm^2$. The UV photoresist was exposed through the mask.

An exposure time was 5 min. After development, the relief pattern was measured by AFM. A cross-sectional pattern of the obtained relief is shown in Fig. 6. The pattern was a sawtooth-like shape. The relief height was about 20 nm. This height is not sufficient to give high diffraction efficiency and should be magnified by one order. On top of that, some microstructure was observed on the relief surface. We are now under theoretical and experimental work to obtain deeper and smoother sawtooth pattern.

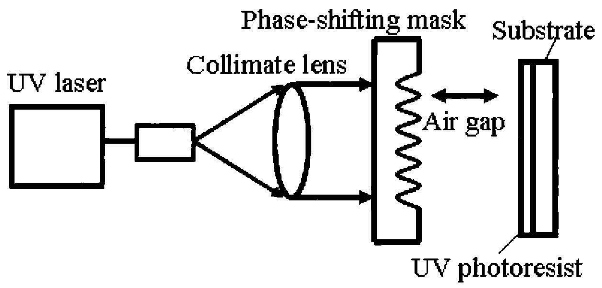


Fig. 5 Exposure layout with phase-shifting mask.

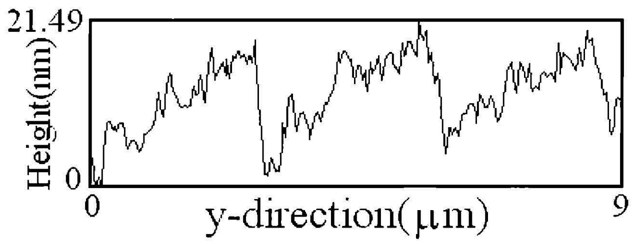


Fig. 6 Cross-sectional profile of the obtained resist grating.

6. Conclusions

A proposed interference exposure system using a phase-shifting mask was discussed for fabricating blazed grating. Fabrication of sawtooth-like relief pattern by using a phase-shifting mask was demonstrated for the first time. Non-contact exposure through a phase-shifting mask provides advantages in simple layout, high yield, damage or contamination free, etc. A phase-shifting mask for 3 μm period grating was designed and fabricated. A sawtooth optical intensity profile was demonstrated. A UV photoresist was exposed through the mask which was carefully aligned and fixed. We obtained a sawtooth-like relief pattern although the pattern depth was not sufficient and should be improved.

We would like to thank Prof. Y. Ono in Ritsumeikan Univ. for his useful comments on holographic exposure techniques. This work was carried out in Next-generation Nanostructured Photonic Device and Process Technology as part of Program to Create an Innovative Components Industry supported by New Energy and Industrial Technology Development Organization (NEDO).

7. References

1) T. Fujita, H. Nishihara, and J. Koyama: Opt. Lett. **7** (1982) 578.
2) T. Shiono, T. Hamamoto, and K. Takahara: Appl. Opt. **41** (2002) 2390.
3) Y. Aoyagi and S. Namba: Jpn. J. Appl. Phys. **15** (1976) 721.
4) Y. Oppliger, P. Sixt, J. M. Stauffer, J. M. Mayor, P. Regnault, and G. Voirin: Microelectron. Eng. **23** (1994) 449.
5) W. Henke, W. Hoppel, H.-J. Quenzer, P. Staudt-Fischbach, and B. Wagner: Jpn. J. Appl. Phys. **33** (1994) 6809.
6) T. J. Suleski and D. C. O'Shea: Appl. Opt. **34** (1995) 7507.
7) N. K. Sheridon: Appl. Phys. Lett. **12** (1968) 316.
8) H. Nagata and M. Kishi: Proc. ICO Conf. Optical Methods in Scientific and Industrial; Measurements, Tokyo, 1974, Jpn. J. Appl. Phys. **14** (1974) Suppl. 14-1, p. 181.
9) R. C. McPherdran, I. J. Wilson, and M. D. Waterworth: Opt. Laser Technol. **5** (1973) 166.
10) G. Schmahl: J. Spectrosc. Soc. Jpn. **23** (1974) Suppl. 1, p. 3.
11) S. Ura, K. Kintaka, H. Awazu, K. Nishio, Y. Awatsuji, and J. Nishii: Appl. Phys. Express **1** (2008) 022005.
12) H. Awazu, K. Kintaka, H. Awazu, K. Nishio, Y. Awatsuji, S. Ura and J. Nishii: Tech. Dig. 15th Microoptics Conf., 2009, p. 192.
13) S. Ura, K. Kintaka, H. Awazu, K. Nishio, Y. Awatsuji and J. Nishii: 7th Int. Conf. Optics-photonics Design and Fabrication, Yokohama, Japan, April 19-21, 2010, 20PSa-62.
14) S. Ura, K. Kintaka, H. Awazu, Y. Awatsuji, and J. Nishii: Opt. Pev. **18** (2011) 99.