Production Optimization of Narrow Pitch Grating Fabrication using Near-Field Holographic Technique

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Abstract: Fabrication of narrow pitch grating for optical communication has been optimized using Near Field Holographic technique. Grating phase mask with pitch period of 240 nm has been used to produce grating patterns in photo resist on Si substrates using the i-line of a conventional mercury lamp as exposure light. Control of duty cycle and uniformity of the near-field holographic gratings have been demonstrated. The technique as a fabrication tool is discussed.
OCIS codes: (230.1950) Diffraction gratings; (220.3740) Lithography; (220.4000) Microstructure fabrication; (60.4510) Optical communications

1. Introduction

The constantly increasing use of digital communication demands new technologies to enhance the data capacity of optical fibers. This can be achieved by increasing the time multiplexing of the signal and/or use more than one wavelength for optical telecommunication. In the latter case the near-field holographic is a promising technique for the production of very precise gratings on wafers for DFB and DBR laser manufacturing. This technology has distinct production advantages over grating fabrication by direct holography or direct e-beam technology. The important features are: Pitches down to 200 nm, free of stitching errors, high yield, optimized to required wavelength, period accuracy better than 0.1 Å, very low duty cycle variation. In the presented work the NFH technique has been optimized and demonstrated using 2-inch Si substrates. A one-inch phase mask of pitch 240 nm was used to print one-inch gratings in photo resist. The profile is investigated using scanning electron microscopy (SEM) and atomic force microscopy (AFM). The homogeneity of the printed gratings was verified using diffraction efficiency scans.

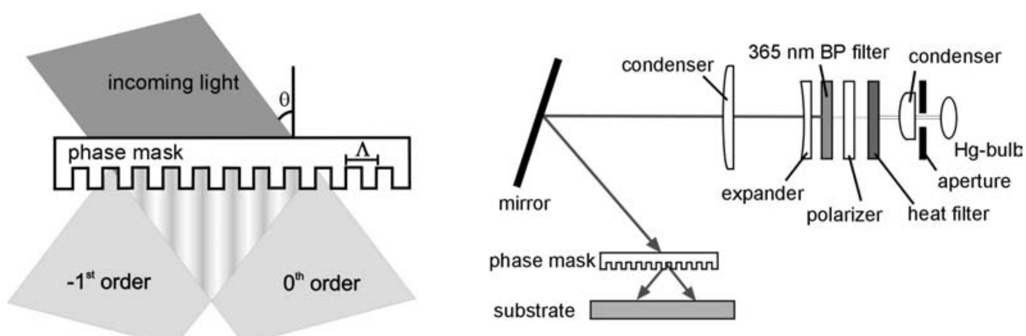

Fig. 1. Sketch to the left of the NFH-technique of printing a grating pattern into photo resist by interference of transmitted 0^{th} and -1^{st} order beams. The incident angle θ is determined by the Bragg condition: $2\,\Lambda\,\sin\theta = \lambda$, where λ is the wavelength of the incoming light and Λ is the pitch of the grating. Schematic setup to the right of the modified mask aligner used in the NFH-printing.

2. Experiments and results

The principle of the near-field holographic (NFH) printing technique is the use of a phase mask capable of diffracting an incoming light beam into two transmitted beams of different orders (0^{th} and -1^{st}). Interference between these beams creates an intensity pattern with a pitch equal to the period of the phase mask as illustrated in Fig. 1.

The generated intensity pattern is exposed to photo resist that subsequently is developed leaving a resist mask for grating etching [1]. The NFH-printing was conducted using a modified conventional mask aligner, MA4, from Suss MicroTec equipped with a mercury arc lamp, collimation lenses, 365 nm filter, 240 nm one-inch phase mask and a polarizer to obtain s-polarized light, see Fig. 1. The light was incident on the phase mask at an angle of 49.5°. The delivered intensity was approximately 20 μWcm^{-2}.The presence of the substrate below the phase mask induces additional interference patterns in the photo-resist created by superposition of the reflected light from the substrate and the diffracted light.

A visual comparison of the developed gratings in the resist-BARLi-Si substrates with and without optimal layer thicknesses is illustrated in Fig. 2. The appearance of additional and undesirable pattern is obvious. This pattern is termed Newton fringes.

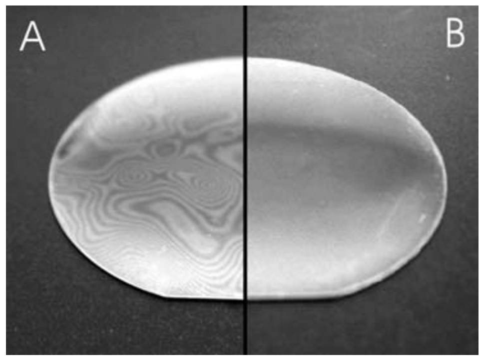

Fig. 2. Developed substrates illustrating the importance of layer optimization. Image A shows a substrate with Newton fringes, i.e. no layer optimization has been employed, whereas image B shows a layer-optimized substrate with no appearance of Newton fringes. The substrates are seen in reddish light.

2.2. Profile of the developed resist grating

The profile of the developed resist grating was investigated using scanning electron microscopy (SEM) and atomic force microscopy (AFM). Fig. 4 and Fig. 5 show images of resist gratings on BARLi-Si substrates for various delivered exposure energy densities recorded by SEM and AFM, respectively. For SEM studies the substrates were cleaved and coated by a thin layer of gold. The profiles are seen to be rounded square-shaped gratings with steep sidewalls. The duty cycle is observed to decrease as the exposure energy increases. The same property is also seen for the profile height indicating that the visibility is less than 100%. See Table 1.

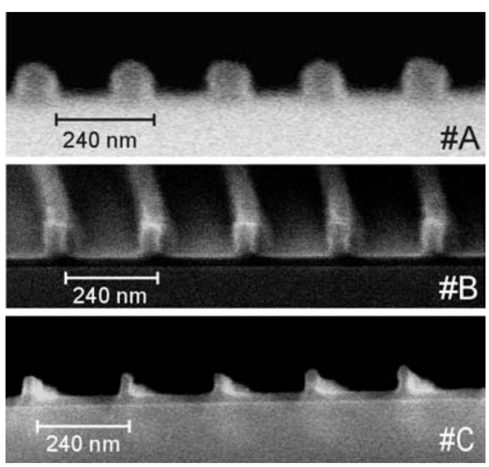

Fig. 4. SEM images of developed resist gratings on BARLi-Si-substrates for different exposure energy densities. The duty cycle for the various gratings decreases as the energy density increases. Images A, B and C show the result after 6.0, 7.0 and 8.0 $mJcm^{-2}$, respectively. The grating is produced by illuminating a 240 nm phase mask using the i-line of the mercury lamp.

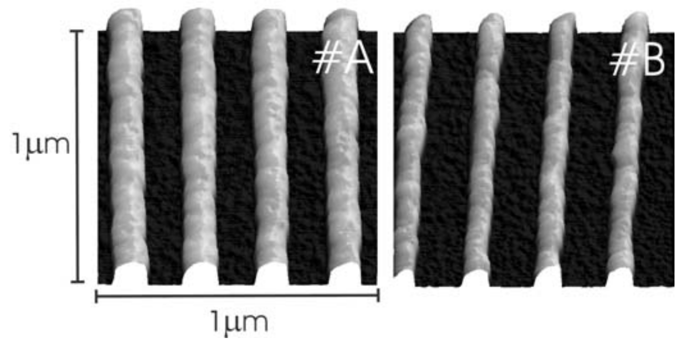

Fig. 5. AFM images of the same substrates (#A and #B) as described in Fig 3.

2.3. Homogeneity of the developed grating

The diffraction efficiency (DE) of a grating has a strong dependence on the grating profile, e.g. duty cycle, profile height and pitch. A change of the profile is reflected in a change of the DE, which in turn provide us with a tool to test the homogeneity of the printed grating.

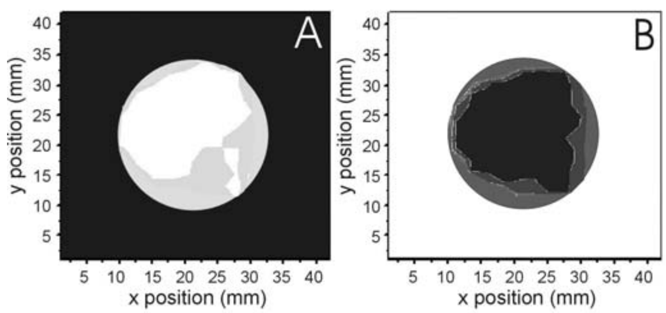

Fig. 6. Scanned diffraction efficiency for -1^{st} (A) and 0^{th} (B) diffracted orders from a one-inch 240 nm grating developed in resist on Si (substrate #A). The wavelength and incident angle of the probe beam were 365 nm and 49.5°, respectively (Bragg condition). The scan resolution was 1 mm by 1mm. The scans illustrate the homogeneity of the printed grating. Contour lines represent 5% variation in efficiency. White corresponds to 30% in plot A and black corresponds to 17% in plot B.

The DE was measured over the grating area. The result is presented in Fig. 6 as contour plots. The measured and calculated DEs are listed in Table 1. The calculated DE is obtained from a program, GSolver, based on rigorous diffraction theory [2]. A square-shaped grating profile was assumed in this calculation. The input parameters were duty cycles; pitch and profile heights extracted from the SEM and AFM images. The DE of the printed gratings in Table 1 is observed to be sensitive to the profile leading to the conclusion that the printed grating indeed is uniform over the grating area with an almost square-shape profile.

Substrate ID		#A	#B	#C
Exposure energy density ($mJcm^{-2}$)		6.0	7.0	8.0
Duty cycle (%)		45	22	15
Profile height (nm)		97	77	55
Diffraction efficiency	0^{th} order	0.17 (0.013)	0.03 (0.007)	0.06 (0.010)
	-1^{st} order	0.30 (0.017)	0.22 (0.013)	0.18 (0.014)

Table 1. Duty cycle, profile height and diffraction efficiencies of developed resist grating for various delivered exposure energy densities. The grating profile data is based on AFM and SEM. The presented diffraction efficiencies are measured and calculated in both the diffracted orders. The calculated values are in parentheses.

3. Discussion and conclusion

The work has demonstrated that it is possible to produce high quality gratings in resist on Si substrates with an almost square-shaped profile using near-field holography printing technique. Furthermore it has been demonstrated that it is possible to produce uniform gratings with almost square shaped profiles with different duty cycles by controlling the exposure energy. Recently, we have optimized and demonstrated the NFH-technique for InP and glass substrates at Ibsen Photonics, these results will be published elsewhere. Near-field holography therefore has a high potential as a production method for narrow pitched gratings.

[1] D.M. Tennant, T.L. Koch, P.P. Mulgrew, R.P. Gnall, F. Ostermeyer, J-M. Verdiell, "Characterization of near-field holography grating masks for optoelectronics fabricated by electron beam lithography," J. Vac. Sci. Technol. **B** 10**,** 2530-2535 (1992).

[2] Grating Solver Development Company. URL: www.gsolver.com .