Phase masks working in 157 nm wavelength fabricated by immersion interference photolithography

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We demonstrate that phase masks can be made from modified fused silica with a period of 180 nm and ~8 mm long by using immersion interference photolithography. The fabrication process of the phase mask is optimized to generate the largest intensity ratio of diffracted ±1 to 0 order. The phase mask is demonstrated to produce a photoresist pattern with halved period (90 nm) when illuminated with a laser of 157 nm wavelength. The phase masks are also capable of generating two-dimensional patterns of holes and dots and serving as molds for imprint applications. © *2003 American Vacuum Society.* [DOI: 10.1116/1.1625958]

I. INTRODUCTION

According to the SIA's lithography roadmap, F_2 laser lithography is one of the most promising technologies for realizing the next-generation, ultralarge scale integrated devices which have a design rule of less than 70 nm.[1] Though exposure tools are expected to be ready within a few years, they are generally too expensive to be accessible particularly to those resist developers who simply would like to know if a new photoresist could be patterned. Meanwhile, there are some applications that require repetitive structures of tens of nanometers in dimension over a large area such as field emission display, quantum dots, photonic crystals, etc. We propose the utilization of a special phase mask as an alternative to conventional lithography technologies.

The phase mask we discuss here is essentially a phase grating which, when illuminated by a coherent beam, can ideally generate an interference pattern with halved period of the phase mask and with unity contrast resulting from the strongest $+1$ and -1 diffraction orders. The halved-period pattern can be recorded in photoresists or any other photosensitive materials. Therefore, the utilization of such a phase mask has been regarded as a powerful tool to imprint a grating structure inside fiber for optical fiber communication and fiber sensing applications or to imprint on a photoresist to test its printing capability. To fabricate such phase masks, grating period, duty cycle, and etched depth should be accurately controlled.

It is well known that to fabricate such a phase mask with nanometer resolution over a large area is challenging. Traditionally, a phase mask is made by e-beam lithography which is very time consuming and has inherent stitching issues. Here we demonstrate that such nanoscale-period phase masks can be alternatively made by employing immersion interference photolithography (IIPL). The period obtained by conventional interference lithography can be expressed as $\Lambda=\lambda/2\sin\theta$, where λ is the wavelength of the incident beam and θ is the incident angle. However, if the incident medium is liquid, then the period of the interference pattern shall be $\Lambda'=\lambda/(2n_q\sin\theta)$, where n_q is the index of refraction of liquid.

The phase mask having correct depth profile, duty cycle, and period can in turn generate the interference pattern of halved period when illuminated with a laser of the designated wavelength. In addition, when using such a mask, the stringent spatial coherence requirement for interference on a light source is much more relaxed, which is especially helpful when an excimer laser is used.

II. MODELING OF PHASE MASK

Assume a phase mask has the profile of an array of rectangular shapes where the height of each rectangle (or tooth) is d. The relative phase delay caused by the optical path difference as light passes through a phase mask can be expressed as

$$\phi_d=\frac{2\pi}{\lambda}d(\sqrt{(n^2-\sin^2\theta_i)}-\cos\theta_i), \tag{1}$$

where n is the refractive index of phase mask material, λ is the wavelength of light, θ_i is the incident angle, and d is the tooth height.

The simple scalar diffraction theory is used to determine the dependence of diffraction efficiencies of mth order on grating parameters such as duty cycle, tooth height, etc.[2,3] A commercial software *G*-solver based on the rigorous coupled-wave theory[4] is used to simulate the effects of proximity printing, etched profiles, wavelength dependence, etc.

III. EXPERIMENTS

A. Immersion interference photolithography (IIPL)

The schematic diagram of experiment setup for employing IIPL to define a phase mask's period is shown in Fig. 1, in which the grating period Λ is given by

$$\Lambda=\frac{\lambda}{2n_{\text{water}}\cos[\sin^{-1}(n_{\text{water}}^{-1}\sin(\theta_i+\varphi))]}, \tag{2}$$

where λ is the free-space wavelength of interfering beams; n_{water} is the index of refraction of de-ionized (DI) water; φ is the half prism angle; and θ_i is the incident angle of laser

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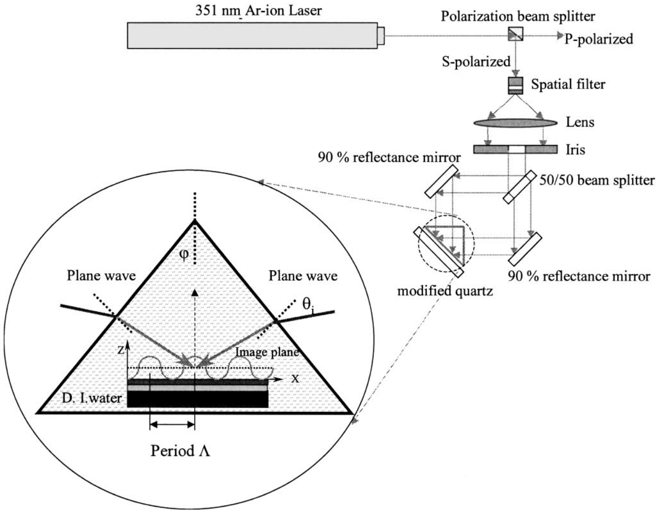


FIG. 1. Immersion interference photolithography exposure system.

beam with respect to the normal of the quartz wall. An ultraviolet (UV) line of 351 nm wavelength from an argon ion laser is used as light source. At this wavelength the DI water has low attenuation, and also owing to its inherent homogeneity, the interference pattern is almost not affected by the existence of DI water.

B. Contrast curves of photoresists

Figure 2 shows the measured contrast curves of *I*-line positive photoresist (EPG510) and direct ultraviolet (DUV) positive photoresist at 351 and 157 nm wavelengths, respectively, for 10 and 1 s development time by using a wet etching solution. Their calculated the contrasts, λ, are 2.95 and 4.04, respectively, for *I*-line and DUV photoresists, respectively. Note that since the DUV positive photoresist is used for 157 nm wavelength exposure, the photoresist thickness is adjusted to ∼50 nm to have enough transmission.

C. Fabrication of phase masks

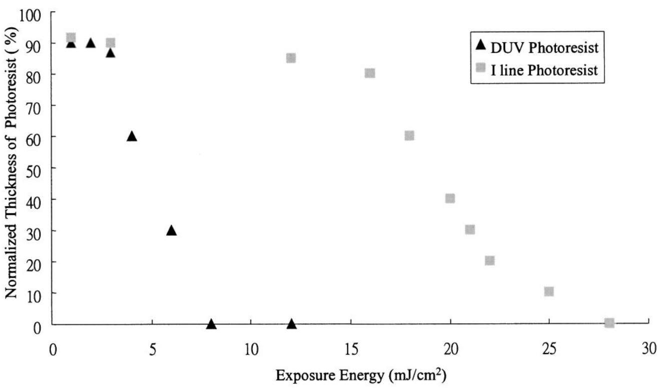


FIG. 2. Contrast curves of *I* line positive photoresist (EPG510) and DUV positive photoresist.

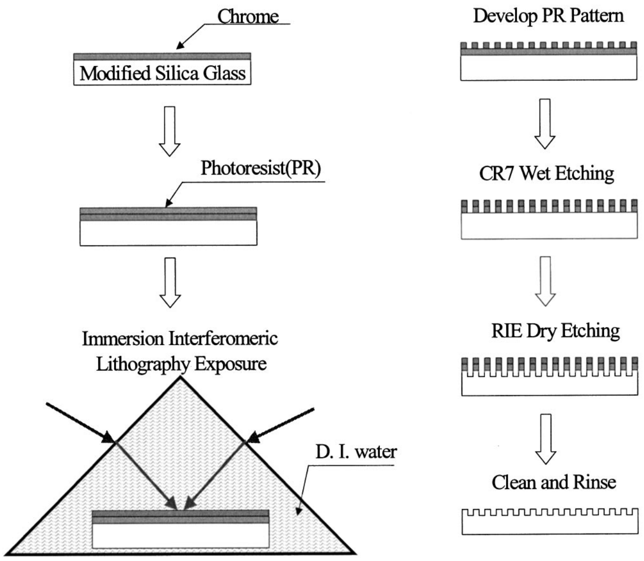


FIG. 3. Processing flow chart of phase mask fabrication.

Modified fused silica is used as phase mask material because of its high transmittance ($>80\%$)[5] at 157 nm wavelength. Additionally, its processing conditions are similar to those applied to normal fused silica. A schematic diagram of phase mask fabrication is shown in Fig. 3. First, the modified fused silica was put into solutions of H_2SO_4, H_2O_2, and H_2O, for thorough cleaning with ultrasonic agitation. We used a chromium layer as a "hard mask" for the modified fused silica substrate. The layer had a thickness of ∼30 nm deposited on the substrate by sputtering. The deposition rate was kept as slow as possible (0.01–0.05 nm/s) so as to achieve better density and anticorrosion. The *I*-line positive photoresist was spun with a thickness of 200 nm, and was then soft baked at 90 °C for 60 s. The resist had an excellent etching selectivity against the chromium layer. IIPL was employed for grating pattern generation. The measured n_{water} was 1.34 at the wavelength of 351 nm. The incident angle could be easily varied to have grating patterns of different periods. In addition, the area containing such fine periods could be very large, basically determined by the size and uniformity of the exposing beam.

After exposure, the sample was treated with a postexposure bake at 110 °C for 60 s to harden and increase the adhesion of the photoresist, and to reduce the line-edge roughness. The photoresist was developed by using a standard developer (tetramethylammonium hydroxide 2.38%) with appropriate development time. After development, the chromium layer was selectively removed in the resist open region by using commercial wet etching solution CR7.

In order to control the etching depth precisely and accurately, the final pattern on the fused silica was obtained by electron cyclotron resonance (ECR) reactive ion etching (RIE)[6,7] according to the following conditions: 2 sccm of Ar, 18 sccm of CHF_3, and 3 sccm of O_2. Under such conditions, an etching rate of 74 nm/min has been achieved. The process enabled a precise etching on the modified silica with a nearly vertical profile and controlled etching depth throughout the entire exposure area. A portion of the phase mask is shown in Fig. 4. The fabrication of the phase masks was completed by

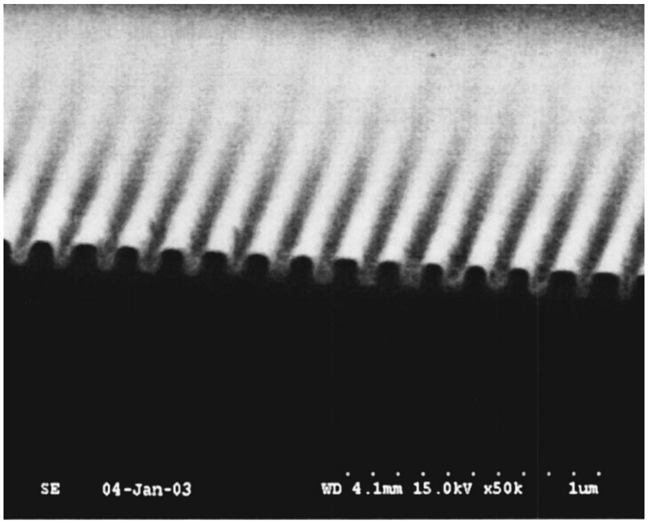


FIG. 4. SEM image of the modified silica glass grating with a period of ~180 nm.

the removal of Cr in a CR7 solution. Finally, we used KOH as a rinse agent to flatten the valley's roughness.

IV. RESULTS AND DISCUSSION

A. Simulated intensity distribution and fabrication of phase mask

Since the duty cycle and the etched depth of a phase mask affect the amount of power diffracted into the first order, a useful figure of merit is defined as $\eta = P_1/P_0$, where P_1 is the power diffracted into the first order and P_0 is the one into the zeroth order. Based on the tool described previously, the simulated three-dimensional (3D) plot of ηs versus duty cycle and etched depth is shown in Fig. 5 for 157 nm exposure wavelength. The results show that to have the largest η we must have a duty cycle close to 0.5. There are two peaks, corresponding to two depths. The larger depth belongs to the phase retardation $\phi_d = 3\pi/2$. For the duty cycle 0.5 and a refractive index 1.67, from Eq. (1), the etched depth will be close to 117.2 nm to have an ideally infinite η, i.e., no power in the zero-order intensity.

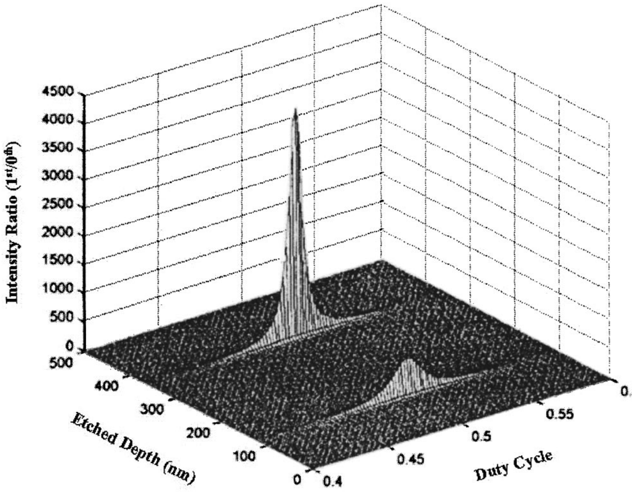


FIG. 5. Calculated zero- to first-order diffraction intensity ratio as a function of duty cycle and etched depth.

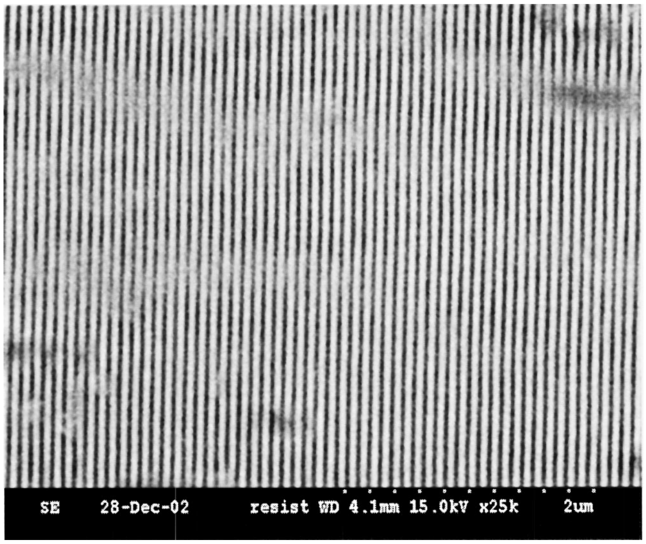


FIG. 6. Photoresist grating pattern of period ~90 nm produced by using the phase mask.

The fabrication of phase masks involves many process parameters. From the accumulated experiences in experiments, we have learned that the most critical four elements are exposure dosage in IIPL, development time of photoresist, chrome wet etching time by CR7, and RIE dry etching time. The optimized process conditions are as follows: the exposure dose was 18 mJ; the photoresist development time was 3 s, the chrome wet etching time was 32 s, and the RIE dry etching time was 91 s.

B. Fabrication of 1D and 2D grating patterns

To demonstrate the effectiveness of utilizing phase masks for 1D and 2D pattern generation, Si wafers were coated with the DUV positive photoresist and an F_2 laser was used

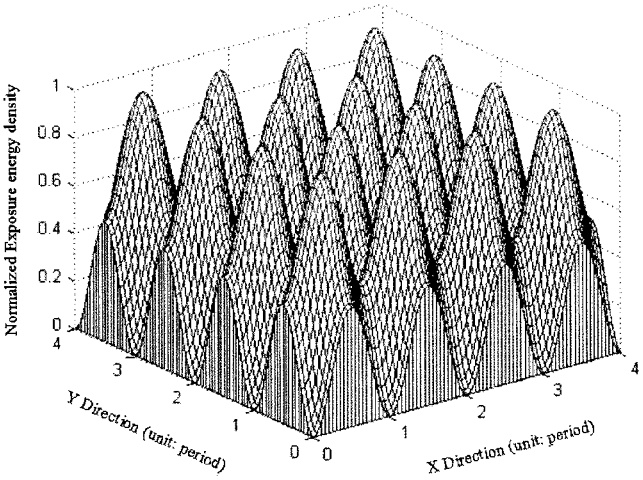
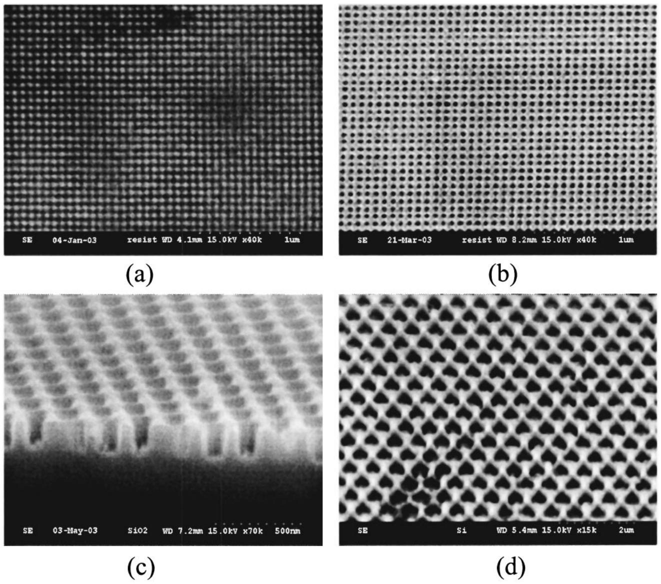


FIG. 7. Simulated distribution of exposure energy density on a photoresist after two successive exposures differing by 90° rotation.

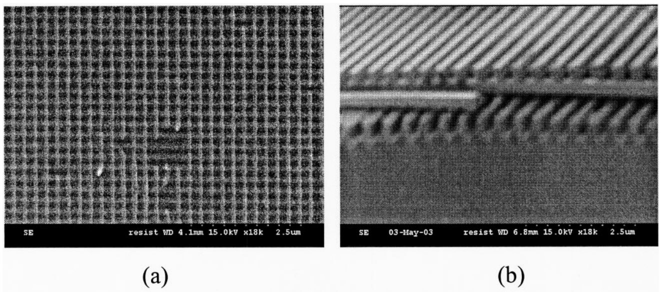


(a) (b) (c) (d)

FIG. 8. 2D photoresist pattern: (a) dots, (b) holes with CD of ~45 nm on a Si substrate, (c) holes on a quartz substrate, and (d) pyramids on a Si substrate.

as exposure light. When the mask was in contact with the photoresist and exposed to 157 nm wavelength, a resist pattern with period halved of the phase mask was observed after development as depicted in Fig. 6. The mask can also be used to generate 2D photoresist patterns if the exposure energy distribution is properly controlled. Figure 7 shows a calculated 2D exposure distribution on the photoresist after two successive exposures but with 90° orientation difference. Therefore, by controlling the level of resultant exposure energy, 2D patterns of holes and dots on the positive photoresist can be formed. Figures 8(a) and 8(b) show 2D dot and hole patterns, respectively. Figure 8(c) shows a 2D hole structure etched on quartz by employing IIPL for exposure and ECR–RIE for etching. Figure 8(d) shows a 2D pyramid structure etched on Si wafer by utilizing IIPL and anisotropic wet etching (solution: KOH, isopropyl alcohol, water).[8]

The phase masks thus fabricated can also be applied to imprint lithography. For example, the pattern of such a phase mask can first be transferred onto polydimethylsiloxane (PDMS) to serve as a mold,[9,10] and then a suitable resist can be imprinted. Figure 9(a) shows a 3D structure of two-layered grating pattern produced on a Si wafer by using PDMS mold of 260 nm period. Figure 9(b) shows a 3D structure of three-layered grating pattern produced on quartz by using a PDMS mold of 0.5 μm period.



(a) (b)

FIG. 9. 3D photoresist grating patterns of: (a) two layer on Si, (b) three layer on quartz.

V. CONCLUSIONS

We have succeeded in fabricating phase masks working in 157 nm wavelength by utilizing immersion interference photolithography instead of conventional e-beam lithography. By employing such phase masks to generate interference patterns halved period and by controlling the exposure energy of the photoresist, 1D grating pattern and 2D patterns of holes and dots on positive photoresist of period ~90 nm are demonstrated. Additionally, these photoresist patterns can be transferred by alternating dry etching and wet etching to achieve various structures on quartz and Si wafer.

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