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Fabrication of Sub-Quarter-Micron Grating Patterns by Employing DUV Holographic Lithography

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Sub-quarter-micron grating patterns with period as fine as $0.22 \mu\text{m}$ have been obtained by combining DUV holographic lithography and silylation technique for the first time. A traditional chemical amplified resist (JSR KRF/K2G) originally working for single layer process at 248 nm wavelength was used for silylation. The silylation selectivity was improved by process control and a photoresist pattern with an aspect ratio of 4 was obtained.

1. INTRODUCTION

Sub-quarter-micron gratings are essential elements for many opto-electronic devices that play key roles in advanced lightwave communication systems. For the InGaAsP lasers operating at 1.3 and $1.55 \mu\text{m}$ wavelength regions where the transmission losses of an optical fiber are low, the first-order grating periods need to be about 0.2 and $0.23 \mu\text{m}$, respectively. There are several methods such as E-beam[1], X-ray[2] and holographic lithography[3,4] for the fabrication of such gratings. Both E-beam and X-ray lithographies are capable of yielding grating periods well below $0.1 \mu\text{m}$ with arbitrary patterns. However, the major concern of E-beam lithography is its low throughput owing to the serial nature of pattern writing. For X-ray lithography, mask problems such as pattern distortion, cleaning and repair have not been resolved. Moreover, both E-beam and X-ray lithographies require very expensive equipment. Conversely, for holographic lithography, no mask or stepper is needed for such regular pattern generation. In addition, the setup involved in holographic lithography is relatively simple to implement if the grating period needs to vary frequently.

In holographic lithography, it is known that interference between the incoming beam and the one reflected from a substrate produces a standing wave pattern in the photoresist layer. For a positive-tone photoresist, an undercut resist profile results if the maximum of the standing wave occurs at the resist/substrate interface and vice versa. Hence, the photoresist pattern is degraded and may cause more problems when transferred to the substrate. Several methods have been shown to solve this problem. For example, one can apply Cr as mask in oxygen reactive ion etching[5] or employ a trilevel resist process with antireflection coating (ARC) as bottom layer[6]. However, these methods involve complicated processes. Here we employed deep UV holographic lithography and silylation process[7-9] to fabricate sub-quarter-micron grating patterns, which has the following advantages. First, an (KrF or ArF) excimer laser has a shorter wavelength and higher intensity than traditional light sources such as Ar^+ and He-Cd lasers; therefore, smaller grating periods can be obtained with one or a few pulses. The mechanical stability of exposure system will not become an issue, and a high pattern contrast can be obtained. Second, the silylation process does not

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need multilayer coating and baking as compared with the trilevel resist process. Third, with top surface imaging, the aerial image does not need to be in focus through the entire resist film and resist can be made highly absorbent in order to reduce reflection. Fourth, the processes of liquid-phase silylation and dry development are compatible with the conventional lithography. Therefore, high resolution and wide processing latitude can be obtained. In addition, a vertical sidewall of photoresist pattern can be obtained because of anisotropic oxygen plasma etching.

2. EXPERIMENT

A KrF excimer laser (Lambda Physik 150T) was utilized as exposure light source which generated pulses of short duration (~ 20 ns) with a rectangular spatial profile (20×10 mm²). Since the coherent length of the KrF excimer laser was short (~ 20 mm), the optical path length difference incurred in the exposure setup shown in Fig. 1 needed a careful control. An attenuator was used to reduce the light intensity to about 14 mJ/cm² before the exposure plane. The incident angle of laser beam, θ_{in} , which determines the pattern period can be adjusted by rotating the mirror. The sample under test was located in the exposure plane. The prism and samples were mounted on a translational stage as an assembly which was then aligned with the laser beam.

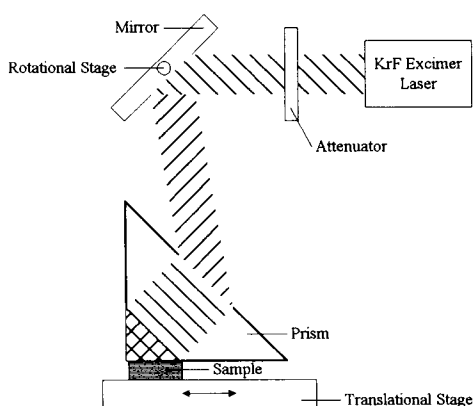


Figure 1. Exposure setup.

The resist we used was one of the chemical amplified resists working at 248 nm (JSR KRF/K2G)[10]. It was spun on a Si substrate at 4000 rpm for 30 sec, resulting in a film thickness of 0.5 μ m. The resist-coated substrate was then softbaked at 80°C for 120 sec. After exposure to the laser beams utilizing the setup mentioned previously, the resist film was post-exposure baked and liquid-phase silylated at room temperature for 120 sec in a beaker. The liquid phase silylation bath consisted of Bis(dimethylamino)methylsilane (B[DMA]MS, 10%) with N-methyl-2-pyrrolidone (NMP, 3%) as diffusion promoter and xylene as solvent. The OH group in the exposed region reacted with silylation agent, and the reaction is illustrated in Fig. 2. After liquid phase silylation, the sample was rinsed with xylene and spun dry. The silylated region then acted as mask in a subsequent dry development.

In contrast to the wet development in a conventional lithography process, an anisotropic O₂ plasma etching is then applied to transfer a silylated image. The RF power of the RIE system (Plasma Lab) was adjusted to 90 W. The oxygen pressure was held at 30 mTorr, and the flow rate was 30 sccm. An etching rate of ~ 130 nm/min was obtained for the photoresist.

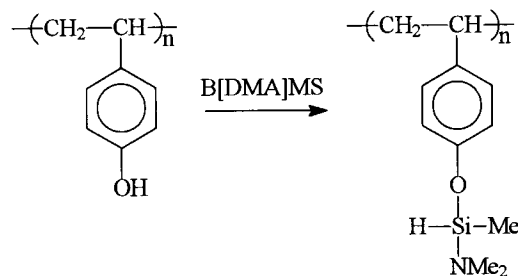


Figure 2. Silylation reaction.

3. RESULTS AND DISCUSSION

During the silylation step, Si was selectively incorporated into the exposed resist area. The Si profile inside the silylated resist was obtained by analyzing the Rutherford backscattering spectrum (RBS). RBS was obtained by using a 2 MeV He⁺ beam and a detector at a backscattering angle of 160

degrees. A typical RBS of a silylated resist is shown in Fig. 3. The large signal increase in signal at the low energy end was due to the substrate Si. The energy at which this occurred varied with resist thickness. Fig. 4 shows a series of spectra for different silylation time. It is shown the silicon uptake increases with time.

The RBS of the resists silylated for 90 sec at different exposures is shown in Fig. 5. The resist was silylated even in an unexposed region. This is due to the partially protected poly(hydroxystyrene) in our resist, which causes the unexposed resist still to contain the OH group. Because the concentration of OH group is higher for an exposed resist, the silylation agent reacts for a longer time with the top surface of exposed resist and thus diffuses less in the direction of thickness. Therefore, for the resist exposed at 35 mJ/cm^2 , the concentration of

incorporated silicon in the upper portion of resist was found higher than that of the unexposed one, but lower in the lower portion. In contrast, due to the inherent but low concentration of OH group in an unexposed resist, the reaction between OH group and silylation agent quickly finished. Hence, no more OH group could react further and then silylation agent continues to diffuse into the lower portion of resist. Therefore, the silicon distribution was observed in the lower portion of the unexposed resist as shown in Fig. 5. Fig. 4 shows more silicon contents in the lower portion of exposed resist when silylation time was longer. Since it was somewhat silylated in the unexposed resist, the silylation selectivity was not good enough. Therefore, to overcome this problem, we have to expose enough energy, i.e. above 30 mJ/cm^2 , to ensure a better silylation selectivity.

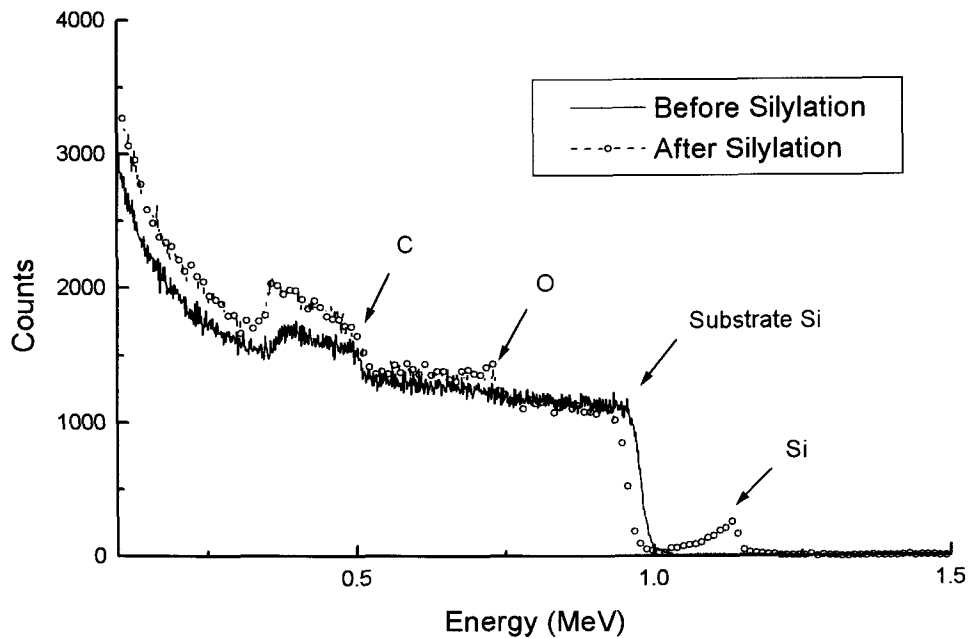


Figure 3. RBS of the resist before and after silylation.

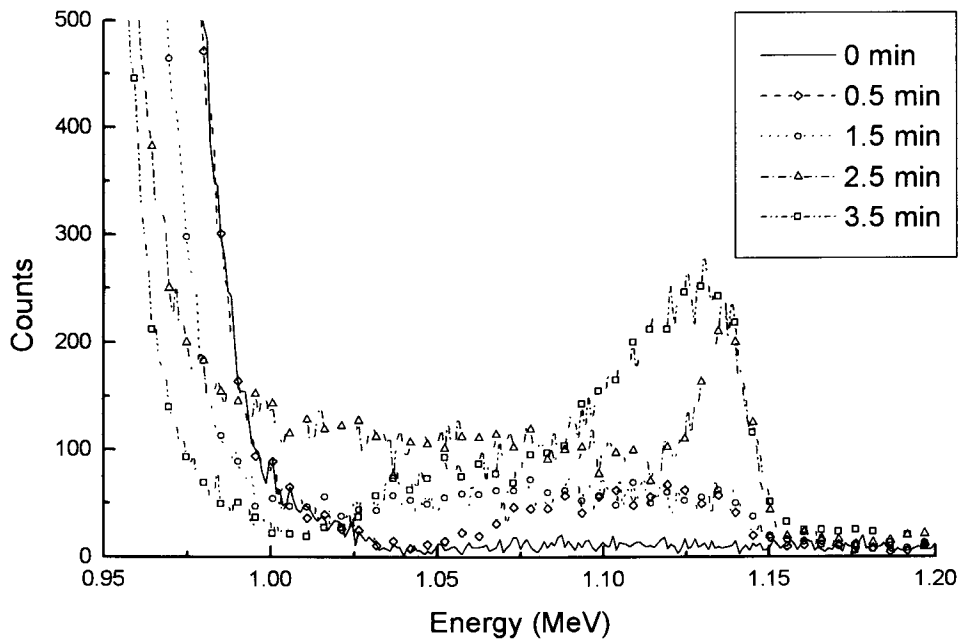


Figure 4. RBS of the resist for various silylation time.

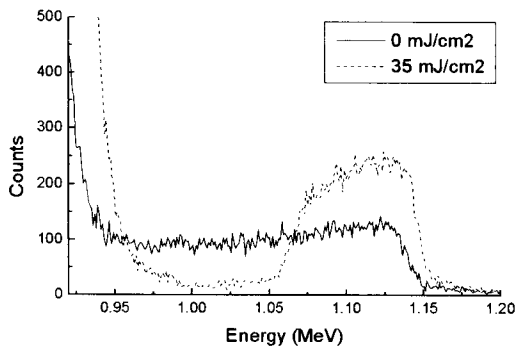


Figure 5. RBS of the silylated resists at different exposures.

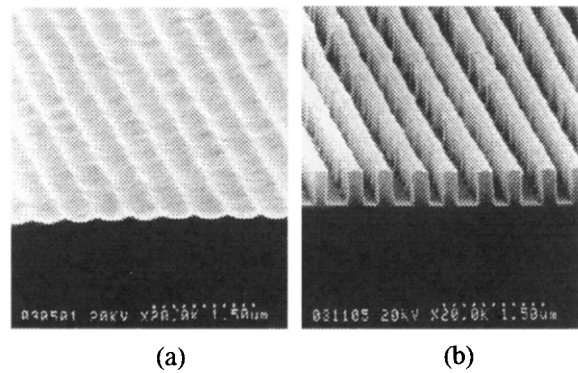


Figure 6. SEM micrographs of sub-quarter-micron L/S resist patterns. Resist was exposed and post-exposure baked at (a) 100°C, 120 sec (b) 140°C, 90 sec.

The temperature of pre-silylation bake (PSB) is an important parameter in the process, which affects the silylation selectivity between exposed and unexposed regions. As shown in Fig. 6, a PSB temperature at 100°C led to low silylation selectivity; however, when the temperature was up to 140°C, the pattern exhibited well resolved and had vertical sidewalls.

Cross-sectional staining of the silylated regions was done by coating gold on the top surface of the resist in order to prevent erosion during the staining, cleaving the sample cross patterned lines, and applying O₂ plasma to the cleaved surface. The silylated profile shown in Fig. 7 was observed by SEM. In the SEM micrographs, we found that it was a little silylated even in the unexposed region. Therefore, we have to apply pre-treatment by using CF₄ plasma to etch away the silylated film in the unexposed region before O₂ plasma development.

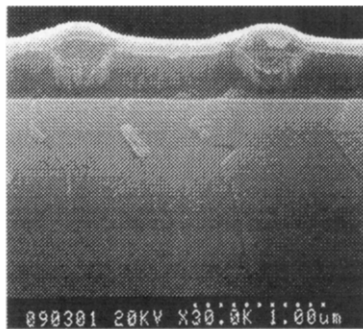


Figure 7. SEM micrograph of silylated profiles.

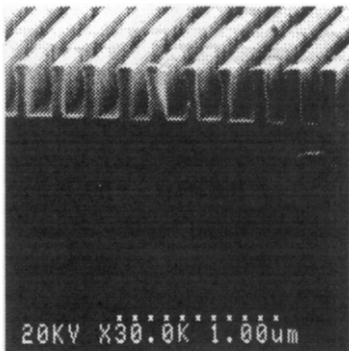


Figure 8. SEM micrograph of a resist pattern with 0.22 μm period and 0.09 μm linewidth.

Shown in Fig. 8 is the resultant grating with a period as small as 0.22 μm, which can serve as a first order grating for a DFB laser operating at 1.55 μm. The linewidth of the photoresist patterns was about 0.09 μm with an aspect ratio of 4, currently limited by the uniformity of laser beam and capability of our RIE system.

4. CONCLUSION

We report for the first time that by combining DUV holographic lithography and silylation, sub-quarter-micron gratings with periods as small as 0.22 μm can be fabricated. A traditional chemical amplified resist working at the wavelength of 248 nm for single layer process can even be used to perform silylation process region. The RBS analysis indicates that this resist was silylated even in an unexposed resist. Enough energy should be applied to ensure a better silylation selectivity, and CF₄ plasma should be applied to etch away the silylated film in the unexposed region before development.

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