Fabrication of fused silica phase gratings with inductively coupled plasma technology

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Inductively coupled plasma (ICP) technology is a new advanced version of dry-etching technology compared with the widely used method of reactive ion etching (RIE). Plasma processing of the ICP technology is complicated due to the mixed reactions among discharge physics, chemistry and surface chemistry. Extensive experiments have been done and microoptical elements have been fabricated successfully, which proved that the ICP technology is very effective in dry etching of microoptical elements. In this paper, we present the detailed fabrication of microoptical fused silica phase gratings with ICP technology. Optimized condition has been found to control the etching process of ICP technology and to improve the etching quality of microoptical elements greatly. With the optimized condition, we have fabricated lots of good gratings with different periods, depths, and duty cycles. The fabricated gratings are very useful in fields such as spectrometer, high-efficient filter in wavelength-division-multiplexing system, etc..

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Micro-optics has received great interest in recent years, and microoptical elements are becoming more and more widely used in optical systems[1−3]. The fabrication procedure of microoptical elements takes the advantages of microelectronics technologies. At first, a mask is fabricated by an e-beam facility or a pattern generator. The second is the lithographic process that transfers the pattern from the mask into a photoresist (PR) layer on a substrate. The last is the etching process during which the substrate is etched with the PR layer or other material layer as the protective layer. Obviously, the last step is very crucial for the successful fabrication of microoptical elements.

In the etching process, wet chemical etching (WCE)[4] or dry etching methods can be used. Generally speaking, dry etching methods have more merits than WCE does. WCE is cheap and fast. The etched depth of the substrate cannot be accurately controlled during the chemical solution etching. Moreover, the undercut effect of WCE greatly affects the vertical etching profile, which determines the performance of microoptical phase gratings. Dry etching is realized in a plasma environment through chemical reactions or physical reactions between ionized erosive gas and substrate. Dry etching methods include reactive ion etching (RIE)[1−3,5], ion milling[6], electron cyclotron resonance (ECR), and inductively coupled plasma (ICP)[7−11], etc. ICP is a plasma system with high density of plasma at low pressure, which could achieve high etch rate and anisotropic etching. An independent radio frequency power is used to control the self-bias voltage of the substrate. Thus, ion bombardment energy on the substrate can be controlled. Because of the above merits, ICP technology in the etching of high-precision microoptical elements should be studied.

The process flow for fabricating a fused silica phase grating is shown in Fig. 1. 1: depositing a chromium layer on the surface of a clean and dry fused silica wafer; 2: coating a positive PR film (Shipley, s1818, USA) on the chromium layer; 3: the photolithographic process of transferring the mask pattern to the PR layer; 4: the developing process and pattern formation on chromium mask by chemical solution; 5: removal of the PR layer by chemical solution and putting the fabricated sample with chromium mask into the ICP equipment for etching; 6: removal of the remaining chromium mask by chemical solution.

The ICP equipment (ICP-98A, Microelectronics R&D Center, Chinese Academy of Sciences) is used in the etching process. Figure 2 is a schematic diagram of the ICP etching system. The system has two independent radio frequency induction sources (RF_1 and RF_2) with the same working frequency of 13.56 MHz. The two RF sources are used to generate the high-density plasma and introduce the self-bias electrical field, respectively. The plasma in the chamber is mostly generated by inductive coupling of RF_1 through a dielectric window. A gas feed ring is located just below the window along the inner edge of the cap. Another independent RF source RF_2 is used to generate the self-bias voltage, and therefore the ion energy of bombarding the substrate can be controlled independently by adjusting the RF_2 power. The plasma chamber is pumped by a turbomolecular pump of 500 liters/second. During the etching process, the sample holder is water cooled to keep the sample near the room temperature. The water-cooling is used to prevent any thermally induced damage on the sample and to maintain a low temperature for a relatively high etch rate. A mixture of CHF_3, Ar, and O_2 is used in the experiments. CHF_3 is the main working gas that produces most of the ions and erosive neutrals. O_2 is mainly used to decompose the polymer to reduce the polymer deposition rate. Ar is used as a buffer gas to keep the plasma stable, and also can increase the etching selectivity of fused silica to photoresist[12].

In the fabrication of microoptical elements with ICP technology, polymer deposition is a frequently encountered problem. Etching and polymer deposition occur at the same time during the whole etching process using fluorocarbon plasma. If the chamber environment is more available for polymer deposition than for etching, the polymer deposition will occur. In the beginning of our study program, some experiments were performed and the results indicate that polymer deposition will

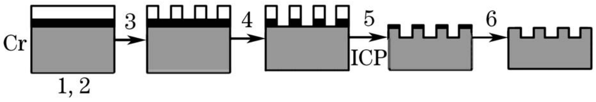

Fig. 1. The process flow for fabricating a fused silica grating with ICP technology.

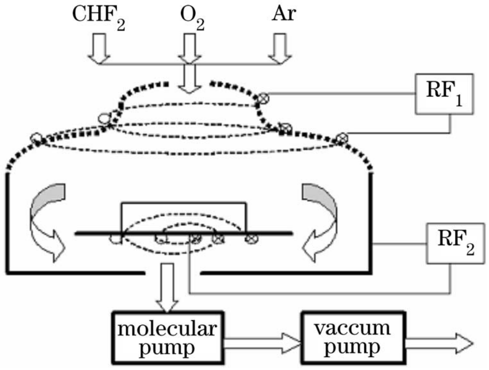

Fig. 2. Schematic diagram of the ICP equipment.

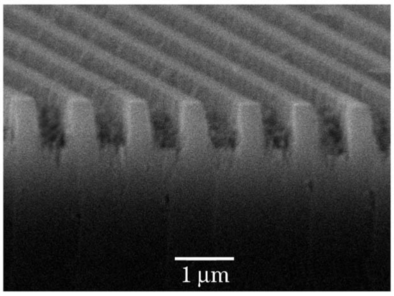

Fig. 3. Cross-sectional image of a holographic surface-relief grating with density of 600 lines/mm (captured by SEM).

affirmatively happen if the total gas flow rate is less than 100 sccm. Polymer deposition can be induced by many factors, and the deposition rate has a close relationship with factors such as the self-bias voltage, the RF powers, the chamber temperature, and the gas flow rate. The gas flow rate directly affects gas resident timeτ[9], which is a very important parameter in the experiment, as described by $\tau = \frac{PV}{Q}$, where P, V and Q are the pressure, the volume of the chamber, and the gas flow rate, respectively. The equation indicates that if the gas flow rate is low, the gas resident time will be long, thus polymer deposition will be more likely to occur. According to the discovered rule, high gas flow rate was employed in the following experiments. Extensive experiments have been carried out, where different gas mixing ratios, different gas flow rates, and different RF powers are used. After the experiments, we obtained the following optimized parameters: 200-sccm CHF_3, 20-sccm Ar, 5-sccm O_2, 700-W RF_1 power, and 200-W RF_2 power. Under the optimized condition, no polymer was found on fabricated gratings.

In optics field, fused silica is an ideal optical material with wide transmitting spectrum ranging from deep ultraviolet to far infrared. Furthermore, fused silica is of high optical quality. Gratings made of fused silica are very useful in high-precision optics field[13−16]. In the following section, we present several fabricated fused silica gratings with different periods and etched depth using ICP etching technology under the optimized condition. Surfaces of all the fabricated gratings are very clean and no polymer is observed.

A grating with a period of 40 μm and a duty cycle of 1:2 was fabricated and its etched profile was measured by Taylor-Hobson equipment (Form Talysurf Series 2) The measured etched depth of the grating is 4 μm. A grating with period of 10 μm and duty cycle of 1:2 has also been fabricated and the etched depth of the grating is about 4 μm, which can be obtained by scanning electron microscopy (SEM). We have also fabricated some gratings with higher density, such as grating with period of 6 μm and duty cycle of 1:2, and the etched depth of the grating is about 3.5 μm. High-density holographic gratings with surface-relief profile have also been fabricated under the optimized etching condition. A grating with density of 600 lines/mm and the duty cycle is 1:2, as shown in Fig. 3. The measured etched depth of the holographic grating is about 1.8 μm. High-density gratings are widely used in high-density optical storage field and optical communication field, etc. In order to achieve deeper etched depth for high-density gratings, more extensive experiments are needed in future.

In conclusion, we have present the detailed fabrication of microoptical fused silica phase gratings with ICP technology. Optimized condition has been found to control the etching process of ICP technology and to improve the etching quality of microoptical elements greatly. Under the optimized condition, we have fabricated lots of good gratings with different periods, depths, and duty cycles. The fabricated gratings are very useful in fields such as spectrometer, high-efficient filter in wavelength-division-multiplexing system.

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