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Transfer of a continuous-relief lenticular array onto a quartz substrate by using SIL combined with the dry-etching method

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Abstract

This study presents the technological process for producing a lenticular array on quartz. With scanning immersion lithography used to define the 3D lenticular array structure on a quartz substrate, inductively coupled plasma-reactive ion etching (ICP-RIE) is able to directly etch the structure. Based on the surface measurement, ICP-RIE can completely etch the surface structure onto the quartz substrate, and the surface roughness can reach 30 nm. Furthermore, after the optical measurement of stereoscopic images, the left and the right stereoscopic images can be successfully transmitted to the corresponding places without crosstalk and with a splitting efficiency close to 80%. As a result, this technology allows for the production of a lenticular structure with various changes on the quartz surface.

(Some figures may appear in colour only in the online journal)

1. Introduction

Quartz is regarded as a high transparency, high intensity and heat-resistant material [1]; however, it is difficult to use the common grinding technique to produce micro-optic elements. Micro-optic elements used to be produced with lithographie galvanoformung abformung (LIGA) [2]. A problem with this kind of processing was that it resulted in accumulated errors that required constant error compensation. Thus, the formation on the quartz was difficult to complete. Technologies that directly etched the structure on the material substrate, such as inductively coupled plasma-reactive ion etching (ICP-RIE), were therefore widely applied to small-sized optic transparent elements (quartz) so as to reduce the procedures of electroforming and molding with LIGA. Dry etching can not only can etch a structure with a high aspect ratio, anisotropic etching does not cause undercutting. ICP-RIE, which is a high-density plasma technique in low pressure, can independently control the ion energy and plasma density [3] and directly etch the 2D photomask on the substrate vertically so as to form a lenticular structure and acquire the favorable surface roughness ($R_a < 30$ nm) and aspect ratio [4].

Nonetheless, a 3D structure on a photomask is required for etching a continuous relief surface structure on a quartz substrate, such as half-spheres, prisms and Fresnel lenses. Generally speaking, gray-scale masks [5–7], E-beams or laser direct writing [8–11] are often utilized to fabricate the 3D structures on the quartz photoresist (PR) for the production of

3D photomasks. However, the production of gray-scale masks requires high energy beam sensitive materials. The production is not only complex, but it is also time-consuming and costly. Although etching with an E-beam or laser direct writing merely requires the regulation of beam energy, the focus is small ($\sim$0.05 μm) and the speed is rather slow [12], thus reducing the speed needed for a large-scale production.

For the first time, the production of lenticular structures with a distinct surface curvature on quartz is proposed in this study. Different from the production of photomask, in scanning immersion lithography (SIL) [13, 14], the 3D structure corresponds to the quartz substrate etched with ICP-RIE. In general moving mask UV lithography, the UV appears diffracted when passing through the pattern slit on the chromium mask. Reducing the gaps between the mask and the photoresist can improve such diffraction, but the shortening of the gap distance could result in surface scratches or even in the lack of mobility [15]. However, matching fluid is added in the moving mask UV lithography to reduce the diffraction error with SIL as well as to increase the numerical aperture (NA) in the exposure, to enhance the resolution of lithography and to reduce surface scratching by being used as the lubricant when scanning. With SIL, a large-scale photomask can be simply and rapidly produced, and the production cost can be reduced.

Recently, the major splitting components have been a parallax barrier and a lenticular [16] because of the prevalence of autostereoscopic display technology. For the applications of micro-projecting stereoscopic systems, a lenticular lens is selected as a small-sized splitting component for the system, and a heat-resistant quartz is chosen to avoid deformation caused by high temperatures. In the experimental process, SIL is first utilized for etching a lenticular array on the quartz photoresist, and then the lenticular array is further etched with ICP-RIE. The lenticular array is placed on the optical system to measure splitting and efficiency.

2. Experiments

2.1. Fabrication setup and results

This study proposed producing a quartz lenticular array without molding by SIL and ICP-RIE to be the splitting component for stereoscopic display technology. Figure 1 shows the production process. First, a 4 μm photoresist (PMER PHA-1300PM, Tokyo Ohka Kogyo Co., Ltd, Japan) was coated on a 4-inch quartz at 6000 rpm, which was further soft-baked at 110 °C for 5 min. Then, it was placed on the SIL platform for photo lithography, where the pattern on the chromium mask presented the curvature radius as 300 μm and the pitch as 200 μm (see figure 1(*a*)). Before exposure, the gap between the chromium mask and the photoresist was controlled at 100 μm, and then the matching fluid (water, $n \sim 1.33$) was added into the gap to reduce the Fresnel diffraction effect [17]. Figure 2 shows the technical diagram of SIL. After scanning and exposure for eight times (20 s a time), 75 ml of the developing agent P7G was utilized and developed 150 s to complete the 5 mm × 5 mm 3D photoresist–lenticular array (see figure 1(*b*)).

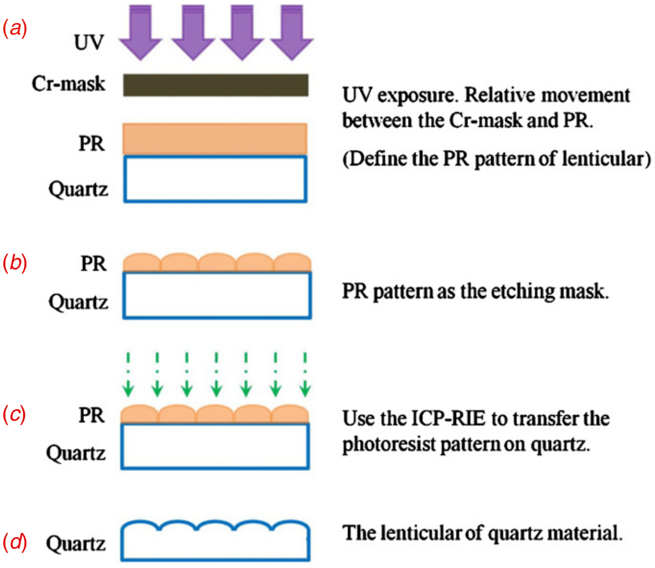


Figure 1. The fabrication process of quartz with a lenticular array profile.

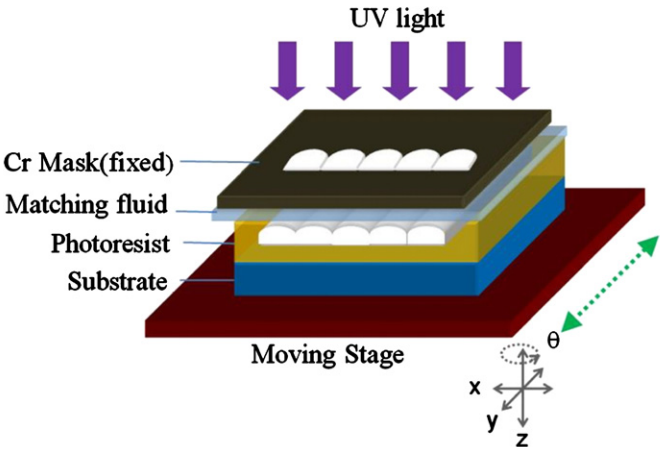
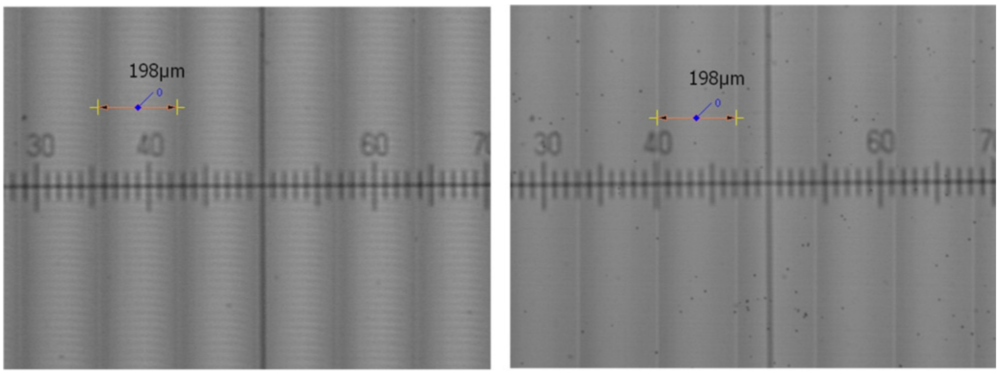


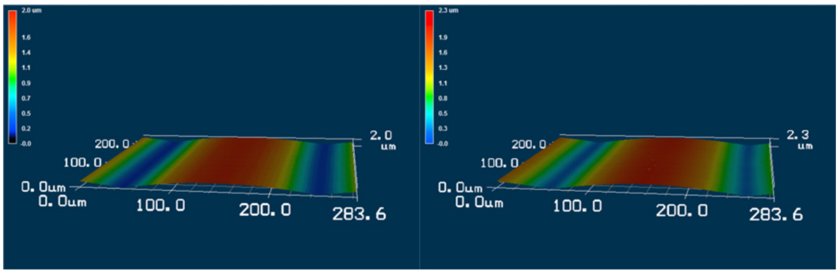
Figure 2. A schematic presentation of scanning immersion lithography.

Furthermore, the above SIL-defined pattern was proceeded by dry etching of ICP-RIE (see figure 1(*c*)), where C_4F_8 was utilized as the etching-protecting gas, and He was added to prevent the quartz substrate from reaching extreme temperatures during etching. When the electrode coil reached a frequency 13.56 MHz, de-ionized C_4F_8 for fluorine plasma ions, the gaseous SiF_4 compound generated from the spontaneous adsorption of fluorine plasma ions and Si materials were removed through a vacuum. Gaseous hydrogen was also added to generate HF with the residual fluorine and was also removed along with the vacuum gas. Meanwhile, positive ions destroyed the Si–O bond, C_4F_8 de-ionized CF_x to form the CF_2 protection film, and anisotropic etching was increased. In the process, the RF power at the bottom was controlled to increase the etching rate of ion bombarding. Finally, the 3D structure on the quartz was successfully etched on the quartz (see figure 1(*d*)). Table 1 lists the parameters for ICP-RIE.



(*a*) (*b*)

Figure 3. The structural surface under a 50× optical microscope, where (*a*) is the photoresist surface and (*b*) the etched structural surface.



(*a*) (*b*)

Figure 4. A 3D structural diagram under laser scanning using the confocal microscope where (*a*) is the photoresist surface and (*b*) is the etched structural surface.

Table 1. ICP-RIE etch parameter.

Items	Parameter
Substrate	Quartz
Gas	C_4F_8/He
Flow rate	12/84 sccm
Pressure	10 m Torr
RF_1 power	1500 W
RF_2 power	120 W
Etch rate	250 nm min^{-1}

Table 2. Average surface roughness of structures with different heights.

Sample	Height (μm)	Photoresist Roughness (R_a) (nm)	Etched Roughness (R_a) (nm)
1	4.0	39	39
2	2.7	38	30
3	2.1	31	20
4	1.8	25	19
5	1.5	22	18

In the fabrication process, an optical microscope was utilized to measure the photoresist surface of the 3D lenticular array produced by SIL and the quartz surface etched with ICP-RIE. The lenticular pitches appeared of the same size at 198 μm (see figure 3). Figure 4 shows the non-contact laser scanning confocal microscope (VK-9700, KEYENCE) used to measure the surface roughness of the lenticular array with different depths before and after etching. As shown in table 2, the structural height of the photoresist presented the average surface roughness of 1.5–4.0 μm to 22–39 nm, while the etched surface roughness revealed 18–39 nm. Apparently, favorable structure transfer and uniformity appear after ICP-RIE. Figure 5 shows the etched surface profile under a scanning electron microscope.

2.2. Spectrum measurement of the lenticular array

For general lenticular stereoscopic displays, the lenticular array is placed in front of a LCD to transmit the left and the right images to both eyes. To verify the splitting effect of the lenticular array in this experiment, a 532 nm laser was selected as a light source, an interlace grating was designed as a left and a right stereoscopic image pair, and the left and the right images appeared on the vertical and horizontal lines, respectively (see figure 6). Figure 7(*a*) shows the splitting results without adding the lenticular array, where the left and the right images overlap and do not appear to split. Nevertheless, the left and the right images could be clearly separated to their corresponding places when the lenticular array was placed behind the interlace grating. That is, the left viewing angle received the vertical lines, the right viewing angle received the horizontal lines and both images did not appear to crosstalk (see figure 7(*b*)). Moreover, the splitting efficiency of the left and the right viewing angles showed results of 77.07% and 78.22%, respectively.

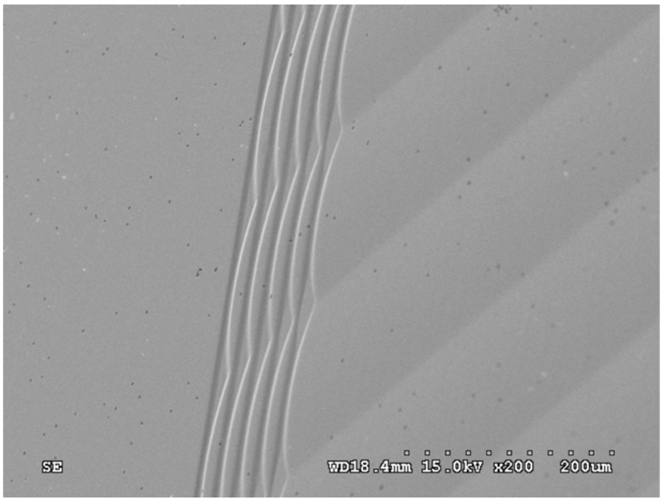


Figure 5. The scanning electron microscope image of a lenticular array.

3. Discussion

This study proposed directly producing a small-scale lenticular array on the quartz for micro-projecting stereoscopic display systems. SIL is, for the first time, utilized for defining the 3D photomask in an experiment. Different from traditional gray-scale masks [5], E-beams or laser direct writing [8], the matching fluid fills the gap between the photoresist and the chromium mask during scanning lithography in order to reduce the diffraction error during exposure and to be the lubricant when scanning. Glycerol (∼1.47) and water (∼1.33) are the common matching fluids in semiconductor processes. Although glycerol presents a higher refractive index, it could increase NA to enhance the resolution, and the high viscosity could result in difficult movements of the carrier so that the 3D structure might be more likely to appear mismatched and also deformation would be likely to occur during the exposure. During overexposure, glycerol is likely to generate bubbles, causing uneven exposure. In this case, water is utilized as the matching fluid, which not only could enhance the stability of the scanning, but also it could even the exposure to produce a smoother surface (see figures 3(*a*) and 4(*a*)). Besides, the minimum exposure resolution could reach 10 μm.

During the etching in ICP-RIE, when the defined 3D lenticular array on the ion bombard quartz has a different etching time on the quartz surface because of the surface curvature, the etched lenticular structure will present curvature. Another problem is that the thickness of the photoresist affects the substrate's heat dissipation during etching. In spite of the fact that He is filled in to cool down the substrate, an overthick photoresist cannot rapidly dissipate heat, thereby causing the adsorption coefficients of carbon products to be affected. The deposition rate at the side of the product structure would be reduced, resulting in isotropic etching. Besides, the thermal velocity of gas molecules in the chamber could easily affect the sticking probability on the surface, causing surface roughness ($R_a > 1$ μm) after formation. What is more, the etching gas flow is in proportion to the etching rate, so that the overflow of C_4F_8 could accelerate the generation of SiF_4 and a polymerization reaction. The deposition on the substrate surface is therefore increased, resulting in a grass phenomenon and affecting the surface roughness. Nonetheless, the decrease of chamber pressure could accelerate the exclusion of polymers from the chamber, so that they would not easily be deposited on the structure surface, and better surface quality and verticality could be achieved. However, less chamber pressure could result in trenching effects. For this reason, a 250 nm min^{-1} etching rate was utilized for etching the lenticular array. Figures 3(*b*) and 4(*b*) show the surface appearance of the etched quartz. Apparently, ICP-RIE can successfully etch a 3D structure produced by SIL to the quartz substrate for a high-transparency

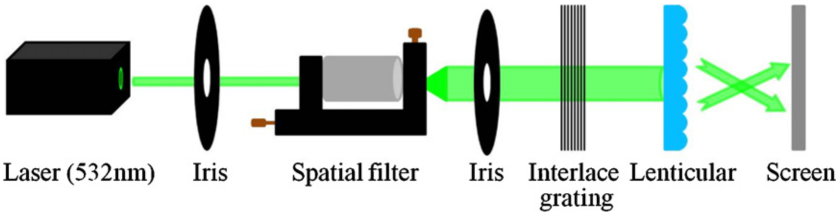


Figure 6. A schematic representation of the optical measuring system.

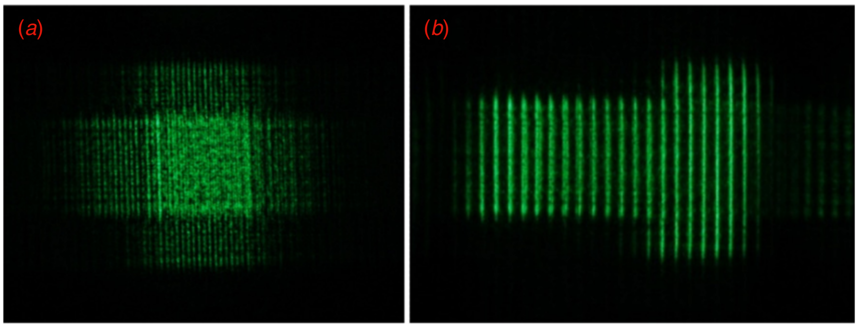


Figure 7. The image results on the screen, where (*a*) is without the lenticular array and (*b*) is with the lenticular array.

lenticular array with the surface roughness reaching 30 nm or less.

The splitting components in stereoscopic projecting systems tend to transmit the left and the right viewing stereoscopic images to both eyes without causing a crosstalk. From the optical splitting experiment, the images with the vertical and horizontal lines are actually separated through the lenticular array, and no overlap appears in between (see figure 7(*b*)).

4. Conclusion

This study successfully applied SIL and ICP-RIE process technology to produce a lenticular array on the quartz. With the filling of a medium liquid and short-time exposure, SIL defined a 3D structure with curvature, accurately controlled the gas flow and the pressure in ICP-RIE chamber, and successfully completed the lenticular array by vertically etching the structure on the quartz substrate. The surface measurement also showed the surface roughness of the etched structure achieving the optical quality ($R_a < 30$ nm), with favorable structure transfer and uniformity. On the other hand, the optic splitting experiment showed the complete separation of the left and the right images without crosstalk. This could be attributed to the splitting component of micro-projecting stereoscopic systems. Consequently, SIL and ICP-RIE could be utilized for micro-optic quartz components with various profiles to reduce the cost and enable rapid production of large-scale structures with favorable optic characteristics.

Acknowledgments

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