Synopsis of
Direct Photolithographic Deforming of Organomodified Siloxane Films for Micro-Optics Fabrication


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1. Introduction
This paper introduces a new technique of fabricating micro-optics by direct photolithographic deforming of hybrid glass films. The technique presented uses mercury UV-lamps and UV-laser exposure of polyethylene-oxide-acrylate modified hybrid glass films to form micro structures to form different micro-optics such as single lenses, lens arrays, and diffraction gratings. The key difference with this reported technique to other hybrid sogel based micro-optics is the elimination of the structure development step with organic solvent which otherwise degrades the surface quality.

2. Hybrid Glass Film Synthesis
The polyethylene-oxide-acrylate hybrid glass films were custom made in-house by the authors. It involves a multi-step complex procedure with specific amounts of a variety of chemicals to prepare the films. The films are composed of “3-(glycidoxypropyl)-trimethoxysilane (GPTMS):silicon tetrachloride (SiCl₄):3-(methacryloxypropyl)-trimethoxysilane (MATMS):methanol (MeOH):dilute hydrochloric acid aqueous solution (0.01 M HCl) in molar ratios of 8:1:8:0.21:26.4, respectively”. In general, the film’s synthesis involves mixing of the aforementioned chemicals, heating, cooling, baking and spin-coating. Specifics on the synthesis procedure can be found in section 2 of the paper. These synthesized films were characterized to have a maximum spectral extinction coefficient of $1.6 \times 10^{-3}$ μm⁻¹ at wavelengths from 450 to 2200 nm. A refractive index of 1.52 was characterized at 632.8nm.

3. Optical Structure Fabrication
Structure fabrication on these hybrid glass films involves exposing the relevant areas with UV light. This UV irradiation was performed using two techniques: a mercury UV lamp with masks and maskless UV-laser. With the first method, two different masks were used: binary and gray-scale. The binary masks were used to shape clear outlines of “different shapes and sizes such as circles and lines” whereas gray-scale masks “were designed to form concave and convex lenses”. The authors used a UV lamp with an irradiance of 10.6 mW/cm² at 365 nm and an exposure level between 2.78 J/cm² and 10.6 mJ/cm². The second irradiation method was performed using a raster laser direct-imaging (LDI) photo-tool with an exposure level ranging between 6 to 30 mJ/cm² at 365 nm. After the exposure, the films were baked at 130°C for an hour. This baking sparks further chemical reaction of the “residual hydroxyl, alkoxy, and epoxy” to form the solid structures, ultimately the lens.

The thermal and chemical stability of these structures were tested to be very good. Elevated temperature up to 150°C for several hours and chemical shock tests with organic solvents, hydrochloric acid and potassium hydroxide base solutions (1 M) did not cause any degradation to the structures.

4. Fabricated Structures
Table 1 is a summary of the fabricated and characterized micro-optical structures by the authors. Figures 1-6 are the corresponding measured surface topography and the cross sectional profile of the structures.
Fig. 1. (a) Diffraction grating surface topography by binary mask. (b) Cross sectional profile.

Table 1. Summary of the Used Masks and Fabricated Structures from [11]

<table>
<thead>
<tr>
<th>Printed Structure</th>
<th>Description of the Photomasks and Exposure Pattern Used in the Experiments</th>
<th>Structural Dimension</th>
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<tr>
<td>Fig. 1: diffraction grating</td>
<td>Binary mask: Clear rectangular areas arranged side by side with linewidth of 35 μm and period of 70 μm (in all other areas outside these features the mask is opaque).</td>
<td>FWHM linewidth, 42.8 μm; FWHM space width, 27.0 μm; p.v. height, 4.46 μm; period, 70 μm.</td>
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<td>Fig. 2: lens array (convex)</td>
<td>Binary mask: Clear circles in array. Circle diameter, 10 μm; center-to-center distance between the adjacent circles, 20 μm (in all other areas outside these features mask is opaque).</td>
<td>Height, 0.87 μm; lens diameter, 10.6 μm.</td>
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<td>Fig. 3: lens array (concave)</td>
<td>Binary mask: Clear circles in array. Circle diameter, 50 μm; center-to-center distance between the adjacent circles, 75 μm (in all other areas outside these features mask is opaque).</td>
<td>Height, 0.70 μm (edge); lens diameter, 54.2 μm; concave depth, 0.13 μm.</td>
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<td>Fig. 4: lens array (convex)</td>
<td>Gray-scale mask: Gray-scale mask is designed to result in a convex-lens-array pattern when negative tone material is used. Size of each lens is 440 μm × 480 μm with no separation between the lenses.</td>
<td>Height, 1.37 μm; lens diameter, 480 μm.</td>
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<tr>
<td>Fig. 5: lens array (concave)</td>
<td>Gray-scale mask: Gray-scale mask is designed to result in a concave-lens-array pattern when negative tone material is used. Size of each lens is 260 μm × 260 μm with no separation between lenses.</td>
<td>Concave depth, 1.26 μm; lens diameter, 260 μm.</td>
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<td>Fig. 6: diffraction grating</td>
<td>UV-laser exposure: No photomask was applied. The Gaussian laser spot diameter was 10 μm. FWHM distributed on 12.7 μm pixel center. The imaged feature size was 50 μm. Exposure dose was 10 mJ/cm².</td>
<td>FWHM linewidth, 61.7 μm; FWHM space width, 42.2 μm; p.v. height, 193 μm; period, 100 μm.</td>
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</table>

Fig. 2. (a) Convex lens array surface topography by binary mask. (b) Cross sectional profile.
Fig. 3. (a) Concave lens array surface topography by binary mask. (b) Cross sectional profile.

Fig. 4. (a) Convex lens array surface topography by grayscale mask. (b) Cross sectional profile.

Fig. 5. (a) Concave lens array surface topography by grayscale mask. (b) Cross sectional profile.

Fig. 6. (a) Diffraction grating surface topography by UV-laser. (b) Cross sectional profile.
5. **Discussion**

With the presented results, a comparison between the binary mask versus grayscale mask and binary mask versus UV-laser can be made. By looking at the cross sectional profiles, we can qualitatively see that this method can be used to fabricate micro-optical structures. However, it seems like the lenses created by the binary masks can only be of small diameters whereas the grayscale masks process seem to allow for larger diameter lenses to be fabricated. This is most likely due to the ability of the grayscale mask to gradually limit the UV exposure from the center of a lens to its edge. Impressively, these lenses were compared with standard Zernike-Polynomials to obtain RMS surface irregularity, with a maximum of 38 nm. Measuring the surface roughness of a small sample region of the structure was found to be at most 4.4 nm.

Comparing the binary mask UV exposed diffraction grating to the UV-laser exposed diffraction grating, we can see a much more uniform sinusoidal variation of its cross sectional profile. This leads to show that the UV-laser process is a much better fabrication technique. No lenses were fabricated via this technique by the authors but based on the high uniformity by the UV-laser, it would certainly be able to fabricate better lenses than the grayscale mask process. The UV-laser method is also provides the flexibility to use different exposure level at different spatial locations compared to the UV exposure method. However, all three different methods produce rounded edges making it only suitable for rounded surfaced micro-optics such as lenses, gratings, and lens array.

The authors stressed that the synthesis process and the design should go hand in hand with using this fabrication technique for micro-optics. A more comprehensive study would need to be undertaken to understand the effects on the structural formation due to the film synthesis formulation. Other variables such as the photoinitiator concentration, exposure level, exposure time and baking temperature would also play a factor in the structure formation. Nonhomogeneity of the film was also cited as a concern by the authors due to the diffusion process. This would need proper understanding and control in order to fabricate a desired micro-optics property.

6. **Conclusion**

The authors have shown a potential technique to fabricate micro-optics. They have also shown that this technique can produce thermally and chemically stable structures. Furthermore, it allows for high surface finish due to the elimination of the development phase of sogel hybrid glass. The LDI UV-laser method is an accurate, simple, fast, and flexible method to fabricate highly accurate micro-optics compared to traditional reflow microlens array which require high tooling and set up costs [2]. With further study to understand all the effects of the different variables, this technique can be a viable micro-optics fabrication means in the future.

7. **References**
