Single step fabrication of microlens arrays with hybrid HfO_2-SiO_2 sol-gel glass on conventional lens surface

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Abstract: We demonstrate a novel method for fabricating glass microlens (arrays) with single step on conventional lens surface. In this method, the glass microlens can be achieved by only one step with sol gel glass material. The microlens aperture and focus length can be controlled easily and uniformly. The fabricated sample shows good focusing property. This work will be useful to improve the performance of compound eyes optical system such as camera, telescope, 3D integral imaging and so on.

OCIS codes: (350.3950) Micro-optics; (160.6060) Sol gel; (220.4000) Microstructure fabrication

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1. Introduction

The number of applications for which microlens are now used has grown so large it is no longer realistic to provide a comprehensive list. However, these applications can be broadly divided into beam shaping, imaging, and coupling. [1] There are many approaches for making lens arrays: (1) ink-jet or microjet processes to form lenses from ultraviolet (UV) or heat curable polymers, (2)hot embossing to imprint lenses in polycarbonate or similar materials,(3) photoresist reflow, via surface tension and dry etch, to pattern lenses with spherical surfaces, and (4) replication of lenses by molding UV curable epoxies against rigid or elastomeric molds. [2,3,4]

However, all these methods are developed to generate microlens on planar substrate, and they are not proper for fabricating microlens on conventional lens (concave or convex) surface. For example, photoresist reflow which is propagated from planar lithography is not proper to pattern on curved surface. Microjet or inkjet with heat or UV curable material, the liquid microlens on curved surface will introduce distortion on microlens when the microlens has apertures of hundred micrometers. Hot embossing or replication of lenses by molding will introduce inhomogeneous deformation in the transfer process from planar substrate to lens surface.

To fabricate microlens on conventional lens surface can prolong the applications of microlens and improve the performance of some optical systems. [5, 6] Kenneth M. Baker demonstrates the method for fabricating photoresist microlens on curved surface by use of a compact holographic projector system. The glass microlens can be achieved by following reactive-ion-etching process. [7]

Recently, we have demonstrated the technique to fabricate gratings on conventional lens surface. [8, 9, 10] In this letters, we demonstrate a novel method which is proper for fabricating hybrid glass microlens on conventional lens surface. In our process, a hydrophilic opening is formed in a hydrophobic background on lens surface firstly, then dispenses the hybrid sol solution and allows a spherical surface to be formed under the effect of surface tension. The glass microlens can be achieved simply by curing.

It is known that the sol-gel material has considerable advantages for the fabrication of micro-optical components because of its good optical properties, cost-effectiveness and good mechanical and chemical stability and high transmission characteristics over a broad wavelength range. Hybrid sol-gel glass technology has been studied as a potential alternative material for realization of high performance microlens elements. [11, 12] By sol gel hybrid glass material, the glass microlens can be achieved by only one step without the transferring of microstructure into substrate. Daniel M. Hartmann fabricated the polymer microlens by use of the hydrophobic effect. [13] The hydrophilic opening is formed in a hydrophobic background by planar lithography, which is not proper to get opening and microlens on curved surface. D.L.MacFarlane fabricated the non-glass microlens on planar substrate by Microjet system. [4, 14] The main differences between their process and our work are the material and substrate to be used to form microlens. The hybrid sol gel glass material used by us can provide us the glass microlens with higher optical property. In our process, we can fabricate microlens directly on many types of substrate, not only the hydrophobic surface, but also the hydrophilic glass one.

2. Fabrication process

Fabrication process begins with the preparation of HfO_2-SiO_2 hybrid sol gel glass. 3-(Trimethoxysilyl)propylmethacrylate(TMSPM(97%) purchased from Gelest; methacrylic acid (99%),n-butanol and Hafnium (IV) t-butoxide (99.999%) are obtained from Aldrich Chemicals and used without any further purification. All the chemicals are stored under argon.

All operations are performed under argon. The preparation of the starting solution used for the film deposition can be described as a three step process. First, 1 mol methacrylic acid is added dropwise under stirring to 80% Hafnium (IV) t-butoxide (1 mol) in n-butanol. Stirring at room temperature is continued for 3h. In a second step, TMSPM is hydrolysed with

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0.01 M aqueous HCL and stirred for 1 hour. Then the two solutions are mixed together (Si/Hf molar ratio of 4:1) and a polycondensation reaction is allowed to occur under stirring for 8h at room temperature. Then the mixed solution becomes the sol. Hafnium is incorporated into a silane network to increase the refractive index and the mechanical stability of the material.

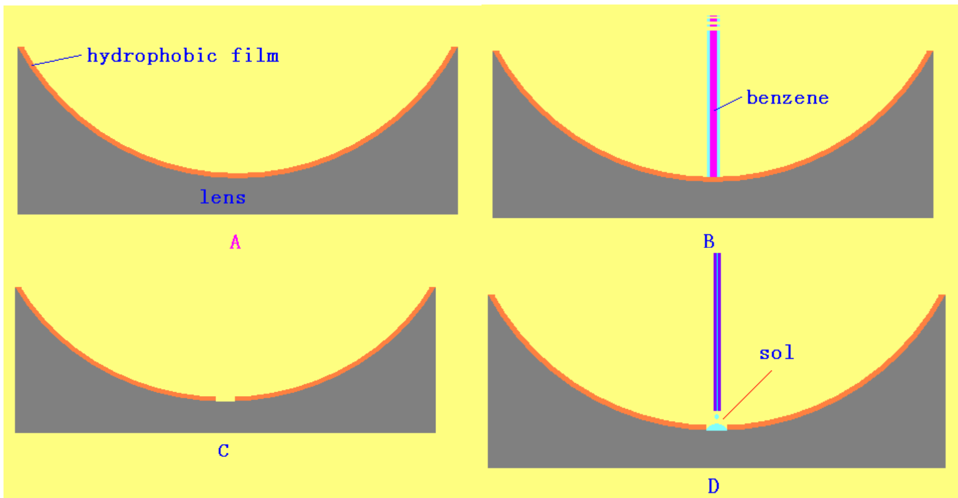


Fig. 1. Fabrication a sol microlens on lens surface.

Firstly, a hydrophobic film is spin coated on the clean lens surface. We select the polydimethylsiloxane as the hydrophobic material. A hydrophobic film with thickness of 0.1 um is achieved on lens surface by spin coating at 4000rpm with 40 seconds. Then put them on the hotplate at 100 centigrade for 30 minutes. Fig. 1(a).

Secondly, put a glass nozzle with a caliber of 300um and benzene in it on the hydrophobic film as shown in Fig. 1(b). The film under the nozzle will dissolve in the toluene and a circular cavity with diameter of 300um will be formed after the nozzle is removed. For the toluene is volatile there will be nothing in the cavity and this cavity will be used as the following microlens aperture. Fig. 1(c).

Thirdly, HfO_2-SiO_2 sol is dispensed in liquid form in the cavity and the sol glass will form a microlens under the surface tension. For the margin of the cavity is hydrophobic, the aperture of microlens will be a constant which is equal to the cavity aperture. The variety of the focal length of the microlens can be achieved by the variety of the volume of the liquid of HfO_2-SiO_2 sol. Fig. 1(d).

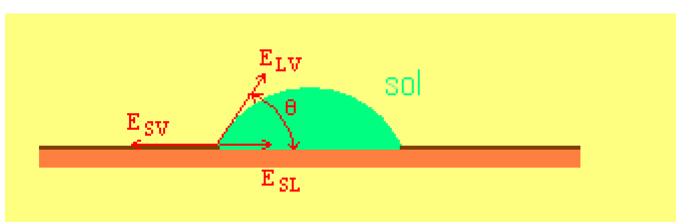


Fig. 2. Contact angle equilibrium

At the hydrophobic margin, there is the equilibrium such that (Fig.2)

$$E_{LV} COS(\theta) = E_{SV} - E_{SL}$$

Where,

E_{LV} is the surface tension of liquid in equilibrium with its saturated vapour.

E_{SV} is the surface tension of solid in equilibrium with the saturated vapour of the liquid.

E_{SL} is the interfacial tension between the solid and the liquid.

θ is the equilibrium contact angle.

The main factors to control the microlens shape are the contact angle and the sol volume. The hydrophobic margin of the cavity is introduced to increase the contact angle ($\theta_{hydrophobic} > \theta_{hydrophilic}$). The purposes in introducing the cavity on the hydrophobic surface include: to fabricate microlens directly on clean hydrophilic glass surface; to increase the adhesion between the microlens and the substrate by removing the hydrophobic film. The hydrophobic film has bad adhesion to glass surface; easily to get other aperture shapes such as rectangle, ellipse, and so on.

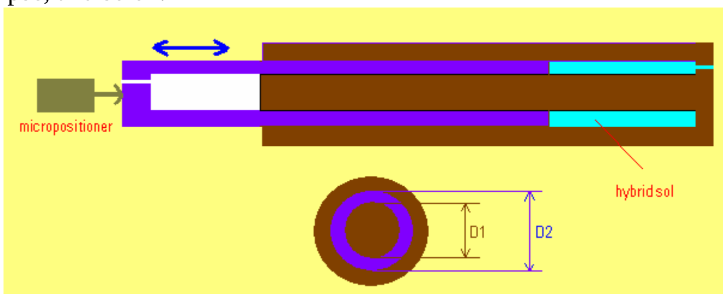


Fig. 3. The method to achieve precise sol volume.

In order to achieve the uniform focal length, the sol volume of every microlens must be controlled precisely. In our process, the micro ring room is introduced to get the precise volume. (Fig.3) The ring piston is drived by the micropositioner at the precision of micrometer. The volume can be achieved by following expressions:

$$V = \left[\pi\left(\frac{D_2}{2}\right)^2 - \pi\left(\frac{D_1}{2}\right)^2\right] \times L$$

Here,

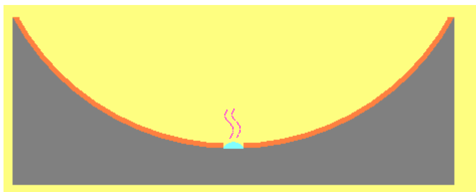
V is the sol volume;

D_2 is the outer diameter of the ring piston;

D_1 is the inner diameter of the ring piston;

L is the displacement of the ring piston.

In our process, D_1 is 0.5mm, D_2 is 1mm. If the ring piston displacement is 1 um, we can get the volume V : 0.58875 nano-litre.



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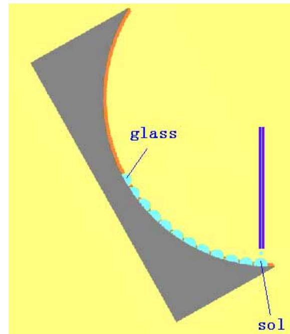
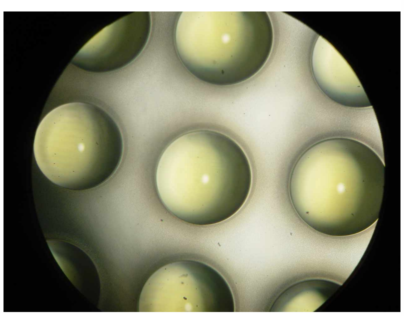


B

Fig. 4. To form the glass microlens and rotate to fabricate microlens arrays on lens surface

Fourthly, after the solvent leaves the sol, the sol becomes the gel. Fig. 4(a). In the fabrication process, in order to improve the solvent evaporation speed, the lens substrate is heated to 120^{o}C, and dispense one microlens every two minutes. The sol needs a few minutes to become gel. When the substrate under the microlens has some significant gradient, tens of minutes have passed, and the sol has become the solid glass. Therefore, the significant gradient of the substrate will not affect the shape of the glass microlens. Fig. 4 (b). The lens is mounted on an XYZ and rotation micropositioner.



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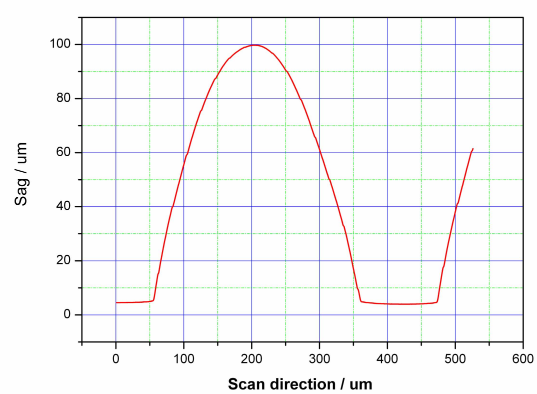

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Fig. 5. Top view and section profile of the microlens.

Using the method described above, a microlens arrays with aperture of 300 um and highness of 95um is fabricated. The fabricated microlens array is shown in Fig. 5. Figure 5(a) shows the top view picture of the fabricated microlenses, and Fig. 5(b) shows the surface profile of the microlens. The average surface roughness value of the HfO_2-SiO_2 hybrid sol gel glass is 0.6nm (root-mean-square value, by AFM) without calcinations and 0.4nm with calcinations (800^{o}C, 3h), providing us a high quality surface. This hybrid glass also displays high crystallisation temperature, which in turn makes them suitable for high temperature applications thanks to their enhanced resistance to the ‘‘thermal shock’’. [14] For some applications with special (damp, solvent) environment the protection film can be considered to be deposited on the glass microlens surface.

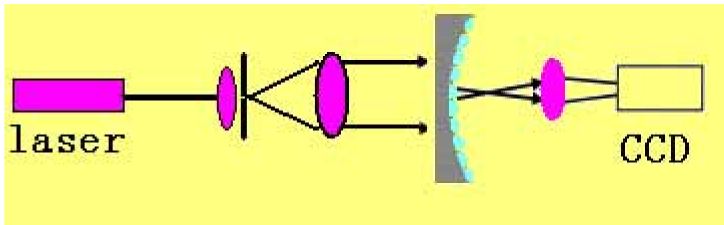
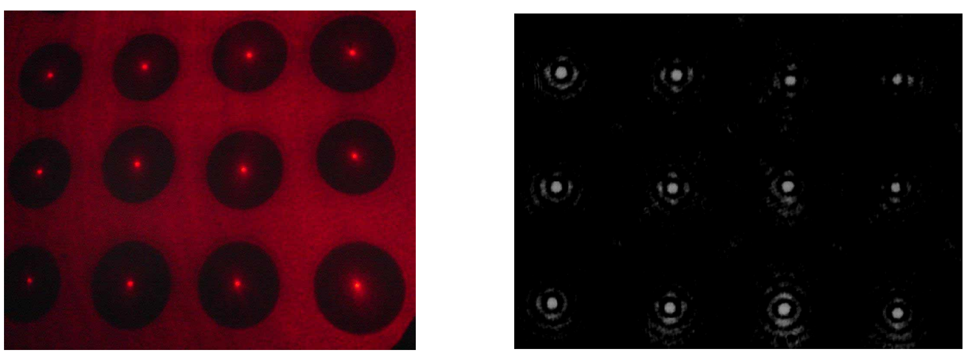


Fig. 6. The optical system to test microlens arrays.

The focusing properties of the individual lenslets are measured using a HeNe laser with wavelength of 632.8nm which is expanded and recollimated as shown in Fig. 6(a) microscope objective after the microlens arrays is used to match to the focal lengths and to image the focal spot. Figure 7(a) shows the focal spot distribution.

We also inspect and character the microlens using the diffraction theory of microlens aberrations. [15] The process is based on the Huygens-Fresnel propagation of a point source through the microlens. The pattern formed by the microlens contains the information of the aberration function of the microlens. This information leads to an interference pattern, which is often expressed theoretically in terms of Zemike polynomials and Bessel functions. Figure 7(b) shows the interference pattern from the microlens arrays charactering the high quality of the microlens. Because the microlens surface is formed by surface tension, it shows high quality focusing property. The aperture of every microlens is a constant, and the volume of the sol is controlled precisely. Therefore, the microlens arraysalso shows uniform focal length.



A **B**

Fig. 7. Focal spot distribution and the interference pattern.

3. Conclusions

There is no doubt that the fabrication of microlens arrays on conventional lens surface is significative to improve the performance of compound eyes optical system, such as camera, telescope, 3D integral imaging and so on. The advantages of this technique include: (1) the fabrication of microlens with glass material, (2) the freedom to control the position, the aperture and the focal length with individual microlens, (3) easy control of aperture and focal length. The disadvantage may be the unsuitability to mass production. The mass production can be achieved by replication of the curved mould with microlens on it by the method described here.

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