Direct photofabrication of focal-length-controlled microlens array using photoinduced migration mechanisms of photosensitive sol-gel hybrid materials

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Abstract: Photosensitive sol-gel hybrid (SGH) materials exhibited the peculiar photoinduced migration behavior of unreacted molecules from unexposed areas to exposed areas by selective UV exposure. Using the photoinduced migration mechanism of the photosensitive SGH materials, the microlens array (MLA) with a smooth surface was directly photofabricated, and the focal length was controlled by changing the photoinduced migration parameters. The higher photoactive monomer content and the thicker film creating a higher curvature produced a smaller focal length of the MLA. Thus, a simple fabrication and easy control of the focal length can be applicable to a fabrication of an efficient MLA.

OCIS codes: (160.6060) Solgel; (220.3630) Lenses; (220.4610) Optical fabrication; (230.4000) Microstructure fabrication; (999.9999) Photosensitivity

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1. Introduction

Microlens arrays (MLA) are important components for beam dispersion and in the conversion for an application of an optical interconnection and of signal processing in compact and complicated optical data storage, sensing, and imaging systems [1-3]. In particular, the control of focusing characteristics including focal length in MLA has received much attention, as it is a crucial factor for exact and efficient beam alignment [4, 5]. MLAs are generally fabricated by methods such as lithography, etching techniques, re-flowing photoresist, isotropic etching substrate, LIGA process, ink-jet, etc. [6-10]. Most methods, however, are often complex and require that several steps are undertaken before the required surface relief structures are revealed. Thus, there are limitations concerning the prospect of a simple, low cost production of desired MLAs with feasible controllability of the focusing characteristics. For these reasons, many studies have concentrated on simplifying the fabrication process of efficient MLAs [3, 11]. The introduction of photosensitive materials, which could be patterned by simple exposure to light, offers the prospect of a considerable improvement over conventional methods. As a result, typical photosensitive materials such as photosensitive inorganic glasses [12] and photopolymers [13] have received attention among researchers. Photosensitive inorganic materials, however, are associated with only small changes in the refractive index and volume, thereby limiting their applications in the direct photofabrication of MLAs. Photopolymers require higher thermal stability and better optical transparency in order to be used in the production of MLAs.

Recently, it has been reported that sol-gel hybrid (SGH) materials exhibit the changes in refractive index or volume on UV exposure and can be simply used for the fabrication of micro-optical elements including MLAs [14-17]. This photosensitivity in SGH materials is highly dependent on the relations between materials compositions and UV wavelengths. Through the control of photosensitivity in SGH materials, various typed micro-optical elements can be fabricated. In particular, photosensitive SGH materials containing large amounts of photoactive molecules exhibit a high enough sensitivity to UV radiation to induce refractive index increase and volume expansion. Moreover, we have recently found the photoinduced migration behavior in photosensitive SGH materials containing large amounts of photoactive molecules. UV exposed areas in photosensitive SGH films experience various photoinduced reactions between the SGH matrix and the photoactive molecules, which causes substantial differences between unexposed and exposed area in the structure, as well as in the concentration of photoactive molecules, diffusibility, molecular size and weight, etc. Subsequently, the migration of unreacted photoactive molecules from the unexposed to exposed areas occurs, changing the configuration of the exposed areas of photosensitive SGH films. This is intimately related to the transport and content of the photoactive molecules, which in turn depends on various parameters, including the UV dose, film composition, film thickness, and the exposed area size. All of these parameters are readily controlled, thus allowing considerable freedom in the design and the surface relief structuring of the directly photofabricated patterns with various sizes and shapes. Thus, for the fabrication of microlenses, the curvature will be changed by controlling the parameters, resulting in control of the focal length. In particular, since the photosensitive SGH materials show photoinduced simultaneous change both in refractive index and volume, a more precise control of the focal length is possible that allows for the fabrication of a high efficiency MLA.

In this study, we thus sought to fabricate a MLA by direct photofabrication using the photoinduced migration mechanism of the photosensitive SGH materials. In particular, it was demonstrated that the curvature of the directly photofabricated MLA is sensitive to the photoinduced migration parameters of the photoactive molecule concentration and film thickness for its focal length to be easily controlled.

2. Experiment

Transparent photosensitive SGH films were prepared using methacryloxypropyl-trimethoxysilane (MPTS, Aldrich), perfluoroalkylsilane (PFAS, Toshiba) and zirconium n-propoxide (ZPO, Aldrich) chelated with methacrylic acid (MAA, Aldrich) as precursors, as described in previous reports [12, 13]. All precursors were hydrolyzed with 0.01-N HCl. After 20 hours of stirring to induce a sol-gel reaction, any residual products such as alcohols were removed at 50°C with an evaporator. Benzyldimethylketal (BDK, Aldrich) as a photoinitiator, and methylmethacylic acid (MMA, Aldrich) as a photoactive monomer, were added into the hybrid solution prior to the coating. The concentration of the BDK was varied from 5% to 25% to examine the effect on the structural evolution of the film surface. Solid BDK was dissolved in 15% of liquid MMA to solve the problem of insolubility of BDK in SGH solution. Also, it was found that MMA enhanced the photosensitivity of the SGH materials by playing a part in photochemical reactions of photopolymerization and photolocking [12, 13]. After the addition of the BDK, the transparent photosensitive SGH solution was filtered through a 0.22 μm filter to remove impurities and bubbles. The photosensitive SGH solution was then used for the direct photofabrication of the MLA.

3. Results and discussion

The direct photofabrication process of the MLA is schematically illustrated in Fig. 1, which shows the typical process of direct photofabrication. First, the photosensitive SGH solutions with various compositions were spin-coated with different spinning speeds on a cleaned glass substrate for 30 seconds. After the formation of films with various compositions and thicknesses, a selective UV exposure was carried out for the optimum exposure time under an Hg UV lamp (Oriel97435, λ = 350~390 nm, optical power density = 70 $mWcm^{-2}$) using a photo mask with MLA patterns with lens of various sizes. After the selective UV exposure with optimum UV doses, the MLAs with the desired shaped were minimally fabricated as a result of the photoinduced migration of photoactive molecules from the unexposed areas to the exposed area in addition to the photochemical reactions without the post treatment of an etching or a developing process. The fabricated MLA was finally stabilized by an additional heat treatment, at 150°C for 3 hours. This stabilization process (i.e. heat treatment) is particularly useful, as it removes from the film the unreacted photoactive monomers in the unexposed area by evaporation. After the heat treatment, the different characteristics of the photoactive molecules, both in the UV-exposed and the unexposed areas, cause significant changes in the refractive index and volume.

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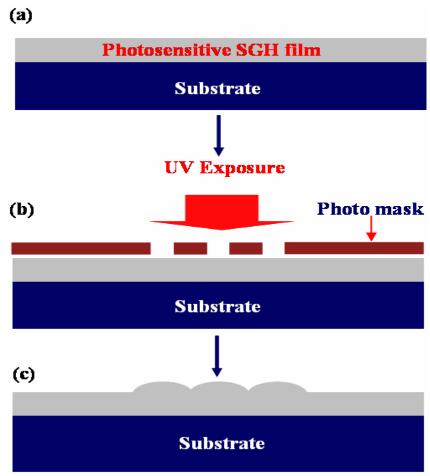

Fig. 1. Schematic diagram of the direct photofabrication of a MLA using photoinduced migration mechanisms photosensitive SGH materials. (a) Spin coating and formation of photosensitive SGH film; (b) Selective UV exposure for the direct photofabrication of the MLA on photosensitive SGH film with a photo mask; and (c) Final formation of the stabilized MLA through thermal curing.

These allow for the fabrication of a stabilized MLA. Thus, the production process of the MLA using the photoinduced migration mechanisms of photosensitive SGH materials is a simple and the cost-effective process, making it desirable for practical applications.

Figure 2 shows (a) a 3D scanning interferometry (SI, SNU-precision, SIS-1200) image, (b) an atomic force microscope (AFM, Park Scientific Instruments, Autoprobe 5 M) RMS roughness image, and (c) a focal spot image on the focusing plane of the directly photofabricated MLA using the photoinduced migration mechanism of the photosensitive SGH materials. As shown in Fig. 2(a), the convex-type MLA with a diameter of 30 μm and the height of 1.25 μm was directly photofabricated using the photosensitive SGH materials containing 15% BDK and 15% MMA exposed to an 84 Jcm^{-2} UV dose. The directly photofabricated MLA exhibits good patternability and a uniform homogeneity, which enables it to function as microlenses as shown in Fig. 2 (c). This relates to the photochemical reactions such as photopolymerization and photolocking of the SGH matrix as well as the photoactive monomers of BDK in MMA. This causes substantial differences between the unexposed and exposed areas in the molecular structure, the concentration of the photoactive monomers, molecular size and weight. Accordingly, the photoinduced migration of the unreacted photoactive monomers and SGH oligosiloxanes from the unexposed areas to the exposed areas occurs and causes a substantial equilibrium. The photochemical reaction and the subsequent photoinduced migration produce a considerable increase in volume as well as a refractive index increase in the exposed area in order to fabricate the convex-type MLA. In order to characterize the performance of the directly photofabricated MLA, the surface roughness was initially measured by AFM in order to analyze the surface quality of the MLA. Top surface of the fabricated lens is very smooth with an RMS roughness of 0.5 nm, as shown in Fig. 2(b). This is due to the use of the simple single-step photopatterning without a development or etching process. The good surface smoothness of the directly photofabricated MLA can be useful in practical applications related to optical communications. In addition, the focusing characteristics at the focal spot of the MLA were measured. The focusing spot intensity distribution of the MLA was measured with a beam profiler using a 1550 nm laser diode source and a charge-coupled device.

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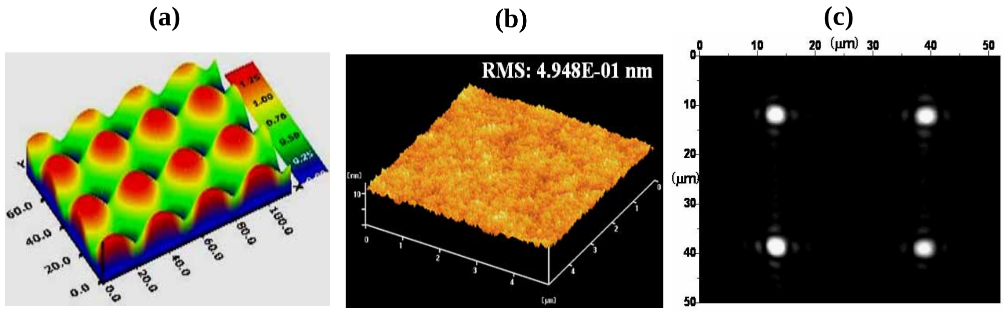

Fig. 2. (a) a 3D SI image, (b) an AFM RMS roughness image and (c) focal spot images on focusing plane of a MLA directly photofabricated using photoinduced migration mechanisms of photosensitive SGH materials.

The spot diameter, based on the $1/e^2$ intensity of the peak and found by fitting a Gaussian to the profile, was 4.1 μm. As shown in Fig. 2(c), the 2x2 array beam image randomly measured on the directly photofabricated MLA exhibits a uniform and good profile. The high performance of the MLA results from the formation of the desired refractive index distribution and surface relief modification via the controlled application of the photoinduced migration mechanism. These fabricated MLAs exhibit the high optical transmission of ~ 95% in the spectral visible and near IR ranges, which can be useful for optical application.

In addition to the optimum UV doses, the photoinduced migration parameters of the photoactive monomer (BDK in MMA) concentration and the film thickness can readily control the sizes and the shapes as well as the refractive index distributions of the MLA. Thus, the focal length of MLA, which is highly dependent on the profiles of both the refractive index and the shape of the MLA, be controlled. Fig. 3 exhibits 2D SI line profiles exhibiting increases in the height of the MLA dependent on (a) the photoactive monomer (BDK in MMA) concentration, and (b) film thickness. The scan size of the SI was 120 μm, and the diameter of the directly photofabricated MLA was approximately 40 μm. The amount of the BDK in the MMA changed from 5% to 25%, and the optimal UV dose utilized was 84 Jcm^{-2}. In addition, the film thickness was controlled within a range of 6.45 μm to 14.89 μm using different spinning speeds. As shown in Fig. 3(a), a greater height of the direct photofabricated MLA is obtained with higher contents of photoactive monomers in the photosensitive SGH film. This is due to the fact that a much larger amount of the monomers in the unexposed area can migrate into the exposed area of the film containing a large quantity of photoactive monomers. In addition, the photochemical reactions, including dimerization, polymerization, and crosslinking reactions of monomers and oligosiloxanes are preferred in accordance with the content of the BDK. Thus, the unreacted MMA and SGH oligosiloxanes together with the unreacted BDK in the photosensitive SGH film can more easily migrate from the unexposed area to the exposed area in the film. As a result, the height of the MLA grows as the photoactive monomer content increases. As can be seen in Fig. 3(b), the height of the directly photofabricated MLA is increased in accordance with the increase in the film thickness. A greater amount of the monomer and the SGH oligosiloxanes in the thicker film is able to migrate into the exposed area, producing a taller MLA. The strong dependence of the photoactive monomer concentration and the film thickness on the height of the directly photofabricated MLA confirms the photoinduced migration mechanism in the photosensitive SGH materials. Thus, the high content of movable monomers caused by the addition of photoactive monomers as well as by a thicker film coating fabricates the MLA with a high curvature of a small focal length.

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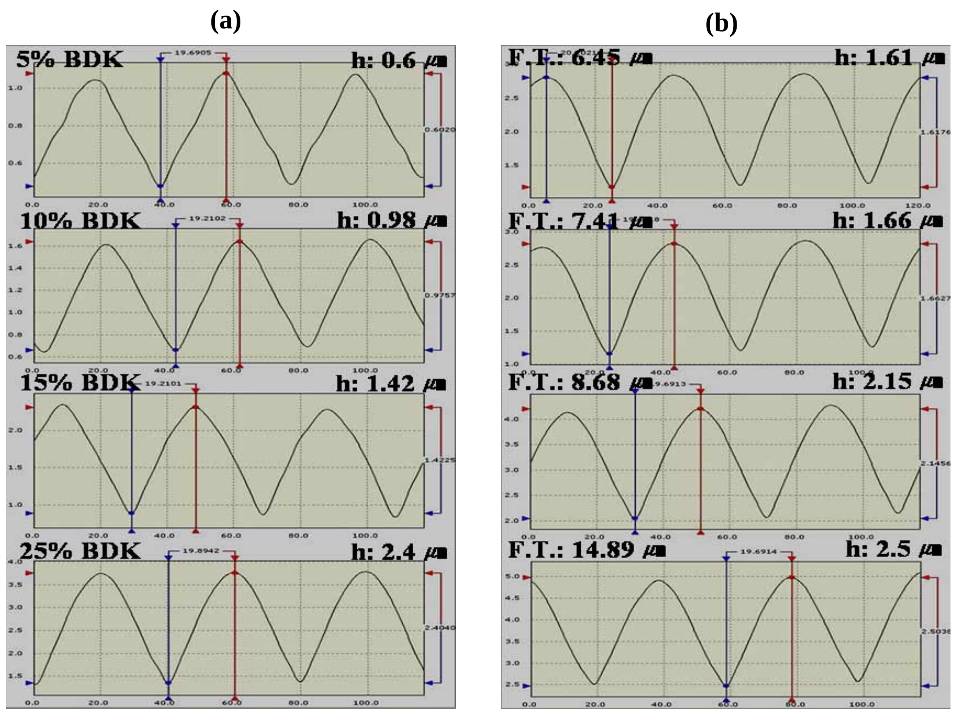

Fig. 3. Height changes of MLAs directly photofabricated through the control of photoinduced migration parameters. 2D SI line profiles of (a) MLA heights depending on photoactive monomer (photoinitiator: BDK) content and (b) MLA heights depending on the photosensitive SGH film thickness. (h: Height of MLA, F. T.: Film Thickness).

Based on the controllability of the curvature of the MLA brought about by changing the photoinduced migration parameters of the photosensitive SGH materials, it was possible to efficiently control the focal lengths of MLAs through the photoinduced migration mechanisms. Fig. 4 exhibits a change in the focal length of directly photofabricated MLAs having 40 μm and 60 μm lens diameters, depending on the BDK concentration and the film thickness increase.

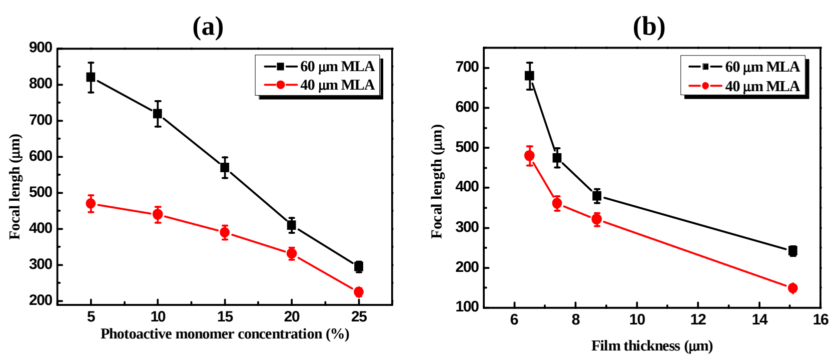

Fig. 4. Control of focal lengths of the MLAs directly photofabricated using photoinduced migration mechanisms of photosensitive SGH materials. (a) The relationship between the photoactive monomer concentration and focal lengths of MLAs. (b) The relationship between the film thickness and focal lengths of MLAs.

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The height of the MLA increases as the BDK concentration and the film thickness increase, as discussed above. In addition, the refractive index distributions on the MLAs would increase by increasing the BDK content and the film thickness due to the photoinduced migration of a large amount of photoactive monomer and the strong photochemical reactions of photopolymerization and the photolocking within the UV-exposed area. The increases of the height and the refractive index changes in the directly fabricated MLAs play an important role in shortening the focal length and enhancing the focusing characteristics. As shown in Fig. 4, the focal length of the directly photofabricated MLA can be controlled easily with changes in the photoinduced migration parameters, particularly the photoactive monomer contents and the film thickness. In addition, an enhancement of the focusing characteristics of beam, such as its homogeneity and intensity, can be obtained by changing these photoinduced migration parameters. Therefore, the simple control of focal length in photosensitive SGH films is shown to be useful for the production of efficient MLAs.

4. Conclusion

In conclusion, a smooth-surfaced MLA was simply fabricated by a direct photofabrication of the photosensitive SGH material using the unique photoinduced migration mechanism. As the photoinduced migration mechanism was highly dependent on the UV dose, photoactive monomer concentration, and film thickness, the height of the directly photofabricated MLA was controlled by changing these parameters. Thus, the focal length of the MLA was controlled to allow considerable freedom in the design and the surface structuring during the fabrication of an efficient MLA.

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