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Fabrication of high fill-factor microlens array using spatially constrained thermal reflow

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ABSTRACT

In this paper, we introduce a simple method for fabricating high fill-factor microlens array using a novel spatially constrained thermal reflow process. The major difference with the conventional methods is that the proposed thermal reflow is conducted in polydimethylsiloxane (PDMS) solution instead of in the air. During the reflow process, PDMS would serve as a barrier to prevent the merging of adjacent microlenses which is usually a big obstacle of achieving high fill-factor in conventional thermal reflow methods. Moreover, for the microlenses are spatially constrained by the PDMS, the reflow process is very stable and much easier to control. To give a good understanding of the process, theoretical models are also established. Experimental results showed that almost 100% fill-factor and relative PDMS soft mold could be obtained efficiently and easily, and the microlens was good in both shape and surface quality. The proposed method may provide a low-cost and accurate method for fabricating high fill-factor microlens array in a very simple way.

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1. Introduction

Microlens array (MLA) has received widespread attention in the past decade because of its great potential applications in image sensors, such as image recorders [1], liquid crystal displays (LCDs) [2], charge-coupled devices (CCDs) [3] and light-emitting diodes (LEDs) [4] etc. To improve the performance of these sensors, as much light as possible should be focused on the photosensitive areas. One of the effective methods of focusing light on the photosensitive areas is to improve the fill-factor of MLA, which can be up to almost 100% and the fill-factor is defined as the percentage of lens area to the total area [5]. And in addition to capture most of the light, high fill-factor microlens array can also effectively avoid stray light effects, which cause unwanted diffraction effects, and capture most incident lights to increase the signal-noise-ratio (SNR) [6].

To achieve high fill-factor MLAs with good profile quality, a number of fabrication methods have been developed, including femtosecond laser technology [7], direct laser writing [8], wet etching [9] and electroplating technique [10] etc. Although these methods have shown their prominent abilities in fabricating MLAs with high fill-factor, there are still some challenges remained to be overcame. For both direct laser writing and femtosecond laser technology, the shape and profile can be precisely controlled. However, expensive equipment costs and low efficiency may hamper their applications for large area MLAs. For wet etching process, through the high fill-factor can be achieved and the depth can be controlled easily, the surface quality and the fabrication efficiency still need to be improved. And for electroplating technique, its applications in fabricating high fill-factor MLAs might be partly limited by long production cycle and uncontrollable thickness. To date, it still remains a problem to develop an accurate fabrication method for MLAs with high fill-factor in an economic and efficient way.

Among the methods for MLAs fabrication, thermal reflow is widely used for the advantages of low-cost, high efficiency and good surface quality. Popovic et al. [11] proposed to fabricate spherical microlens array by melting cylindrical resist when the temperature is above the glass transition temperature (Tg). The MLA after reflow also shows good surface quality. However, there are also some issues which would block further use of this method in image sensors field. Daly et al. [12] found that it was possible to produce MLA with pitches ranging from a few micrometers up to 800 μm with thermal reflow. However, when the pitch of micolens array is smaller than a safe distance, due to surface tension, microlenses will merge with each other, which seriously limits the improvement of fill-factor. In order to avoid the occurrence of the above, Knieling et al. [13] used glass cylinders, which were processed by

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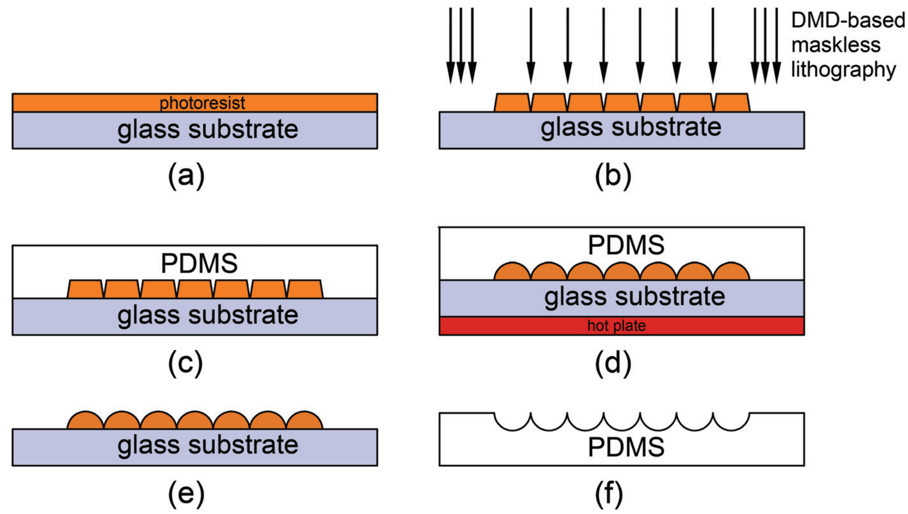

Fig. 1. Schematic diagram of the fabrication process. (a) Photoresist spin coated on a glass substrate. (b) Micro pillar array without gap after exposure and development. (c) The micro pillar array in PDMS solution. (d) The spatially constrained thermal reflow process. (e) Microlens array with almost 100% fill factor on the glass substrate. (f) The PDMS soft mold with concave cavity array.

dry reactive ion etch (RIE) on the glass substrate, as micro barriers to stop the merging phenomenon during reflow process, so the fill factor could be significantly promoted. However, the RIE process is inefficient, and the alignment between the glass and resist cylinders is also a hard work. Hsiharng et al. [14] used precise control of temperature and time to get a square microlens array with high fill-factor. However, it is complicated to fabricate high fill-factor microlens arrays with different requirements when they need different temperature and time control.

In this paper, we demonstrate an efficient, simple, low-cost and high precision method to fabricate MLA with almost 100% fill-factor, by combining DMD (the digital micromirror device) based maskless lithography [15,16] and spatially constrained thermal reflow. Using the sidewall effect in DMD-based lithography, micro pillar array without gap is prepared on glass substrate. Then gapless microlens array will be formed after a thermal reflow process. However, due to the small gaps between micro pillars, the microlenses will stick together during the reflow process. And this will make it very difficult to achieve high fill-factor microlens array in the process. To overcome this obstacle, we introduce a novel spatially constrained thermal reflow method. Different from conventional methods being performed in the air, our process is conducted in the polydimethylsiloxane (PDMS) solution. During the process, the PDMS in the intersection area will serve as a barrier to prevent the merging of micro pillars with very small gap and has little effect on the photoresist pillar reflowing to form microlens. Moreover, for the microlenses are spatially constrained by the PDMS, the flow in the diameter direction on the substrate is also limited efficiently, so the reflow process is very stable and much easier to control compared to the conventional methods. With this simple method, it is easy to achieve MLAs with almost 100% fill factor.

2. Fabrication method

The fabrication process for high fill-factor MLA in this work is illustrated in Fig. 1. The fabrication process began with a spin coating on a glass substrate in which an AZ4620 photoresist film was obtained, as shown in Fig. 1(a). Then, micro pillar array without gap were fabricated through DMD-based maskless lithography, as shown in Fig. 1(b). After exposure and development, PDMS solution was coated on the glass substrate to cover the gapless micro pillar array, self-leveled at ambient temperature for more than 30 min, as shown in Fig. 1(c). The PDMS solution was prepared by mixing the PDMS precursor and curing agent (10:1 wt/wt in our case). Next, the spatially constrained thermal reflow process was conducted on a hot plate (LabTech EH35A plus) in the PDMS solution, just as shown in Fig. 1(d). In order to ensure completely reflow and curing of PDMS, the heating temperature was set to 180 °C, which was above Tg of AZ4620 (115 °C). During this process, the partly cured PDMS could serve as a barrier to stop the merging of photoresist, which made the micro pillar array without gap successfully reflow to MLA with almost 100% fill factor. After natural cooling, the PDMS layer was peeled off from the glass substrate, and we obtained high fill-factor MLA on the glass substrate and the relative soft mold with gapless concave cavity array, as shown in Fig. 1(e) and (f).

The schematic diagram of DMD-based maskless lithography system is shown in Fig. 2. The uniform illumination part is composed of OmniCure^{TM} S1500 with a central wavelength of 365 nm, a high power fiber light guide and an adjustable collimating adapter (EXFO Co., Canada). The DMD (Texas Instruments Co. America) consisted of a 1024 × 768 square micromirrors array with edge of 13.68 μm, plays the same role as the physical mask by generating a dynamic mask in real time. After being modulated by the DMD, the light is projected onto the 3D motorized linear stage through a 0.146× objective lens with an objective numerical aperture of 0.13 (CFI Plan Flour ×4, Nikon Co. Japan). Each focused beam size from one micromirror is approximately 2 μm on the image plane which offers it enough precision for fabricating gapless micro pillar array. By a 3D motorized linear stage (Bocic Co., China), the defocus phenomenon could be avoided effectively and large area fabrication could be performed easily.

3. Theoretical models

Considering that the light projected onto the fabrication stage is not parallel in the DMD-based maskless lithography system and the development exerts a tremendous influence on the side wall [17,18], the micro pillar could be viewed as a truncated cone instead of cylinder, which should be avoided in conventional lithography. However, in this work, we use this feature to fabricate gapless micro pillar array, as shown in Fig. 3(a). In order to get 100% fill-factor MLA, the hexagonal MLA layout is chosen and part of the design digital mask image is shown in Fig. 4. The side of the hexagon a is about 50 μm, and by adjusting the size of gap t from 2 μm to 10 μm, the gapless micro pillar array can be successfully fabricated in our DMD-based maskless lithography system. In the thermal

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