Fabrication of Close-Packed Microlens Array with Superhydrophobicity and High Imaging Performance

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ABSTRACT

Microlens arrays (MLAs) with special functions such as superhydrophobicity and self-cleaning ability are highly desired in the micro-optical system which is often used in easily polluted environment. In this paper, a new method is demonstrated to fabricate the MLAs with a high fill factor and superhydrophobicity. The method combines femtosecond laser wet etching, polydimethylsiloxane (PDMS) replication and subsequently femtosecond laser direct writing process. The fabricated MLAs decorated with micro/nanoscale hierarchical structures compared with the normal MLAs. Water droplets on the as-prepared surfaces exhibit superhydrophobicity and ultralow adhesion which endows the fabricated samples possess self-cleaning property. The as-fabricated MLAs could find their applications in bioscience research, ocean exploration, endoscopic surgery, microfluidic system, etc.

Keywords: microlens array, high fill factor, superhydrophobicity, femtosecond laser microfabrication, anti-water

1. INTRODUCTION

Micro-optical elements, such as microlens array, micro-grating, light modulator and so on, play an important role in the micro-optical system [1-3]. Among these common components, microlens arrays (MLAs) are primarily applied in the biochemical observation [4, 5], artificial compound eyes [6-8], lab-on-chip devices [9-11] because of its small size, and excellent optical imaging ability. There are many methods which have been proposed to fabricated MLAs with smooth surface morphology and great imaging ability including thermal reflow, hot embossing, gray-scale photolithography and laser direct writing, and so on. However, these MLAs with smooth surfaces structures cannot withstand contaminates such as dusts and water droplets. Accumulation of contaminants on the surface of the MLAs will lead to poor optical imaging performance. Furthermore, it may cause the entire optical system to failure. From a practical point of view, the fabrication of the MLAs that have remarkable optical performance and waterproof properties is highly desired.

Many natural surfaces exhibit superhydrophobic and self-cleaning capabilities, such as lotus leaves, mosquito's eyes, moth's eyes, *etc* [12-14]. To mimic these surfaces, there are many fabrication methods which have been reported to achieve superhydrophobicity, such as femtosecond laser direct writing [15-19], template method [20], self-assembly [21], soft lithography [22], chemical etching [21], plasma etching [23], and so on. Among these fabrication methods, building micro/nano structures on the surfaces was demonstrated to be the most effective way to achieved superhydrophobicity. For instance, inspired by lotus leaves, Yong *et al.* achieved superhydrophobic and self-cleaning properties on the PDMS surfaces via femtosecond laser ablation [16]. Hemant *et al* fabricated multiscale arrays by sacrificial layers [24]. However, to the best of our knowledge, endow the MLAs with superhydrophobicity and self-cleaning function has not been reported.

Herein, we present a strategy based on tactfully synthesis of the bio-inspired functional nanostructures possessing special surface properties by learning from the natural biological structures and the optical functions of MLAs. The fabrication of the superhydrophobic MLAs on a PDMS substrate combines femtosecond laser wet etching, template replica and laser direct writing process. The as-prepared MLAs decorated with tens or hundreds of micro/nano particles. The substrate exhibits great superhydrophobicity besides their high imaging performance.

Third International Conference on Photonics and Optical Engineering, edited by Ailing Tian, Proc. of SPIE Vol. 11052, 110520J · © 2019 SPIE · CCC code: 0277-786X/19/$18 · doi: 10.1117/12.2521578

1. EXPERIMENTAL SECTION

2.1 Experimental Process

The whole fabrication process can be divided into four steps: femtosecond laser irradiation, hydrofluoric acid (HF) wet etching, PDMS replication, and laser direct writing (Figure 1). A regenerative amplified Ti: sapphire laser system (Coherent Libra-usp-he) was used to produce femtosecond laser beam (pulse duration: 50 fs; central wavelength: 800 nm; reputation rate: 1 kHz). In the first step, the laser beam was focused on a K9 glass by an objective lens (50 ×, NA=0.6, Nikon) to generate an array of ablated craters. The laser power was set as 5 mW. The distance and exposure time were controlled by the program and the values were set as 55 μm and 400 ms, respectively. After the laser exposure, the sample was immersed into 10% HF solution for about 100 minutes. The square close-packed microlenses can be obtained until the adjacent concave structures "squeezed" each other during the etching process (step 2). Next, the concave MLA-textured sample was used as a template to fabricate convex MLAs (step 3). The PDMS mixture was prepared by blending the prepolymer (DC-184A, Dow Corning Corporation) and curing agent (DC-184B, Dow Corning Corporation) with the volume ratio of 10 : 1. Then the mixture was poured onto the template and cured at 100 ℃ for 90 minutes. Subsequently, the convex MLAs will be obtained by peeling off the PDMS film from the substrate. In the fourth step, the laser beam was focused on the PDMS sample again by an objective lens (50×, NA=0.6, Nikon). Different from point-to-point laser treated manner, the line-by-line method was used to produced hierarchical microstructure on the convex microlens-textured PDMS surface. The laser power, which has significant influence of the surface wettability, was set as 20 mW. The laser scanning speed and the distance of the adjacent laser scanning lines (AD) were changed by the program. After the irradiation, the as-prepared sample was cleaned by acetone, alcohol, deionized water, respectively.

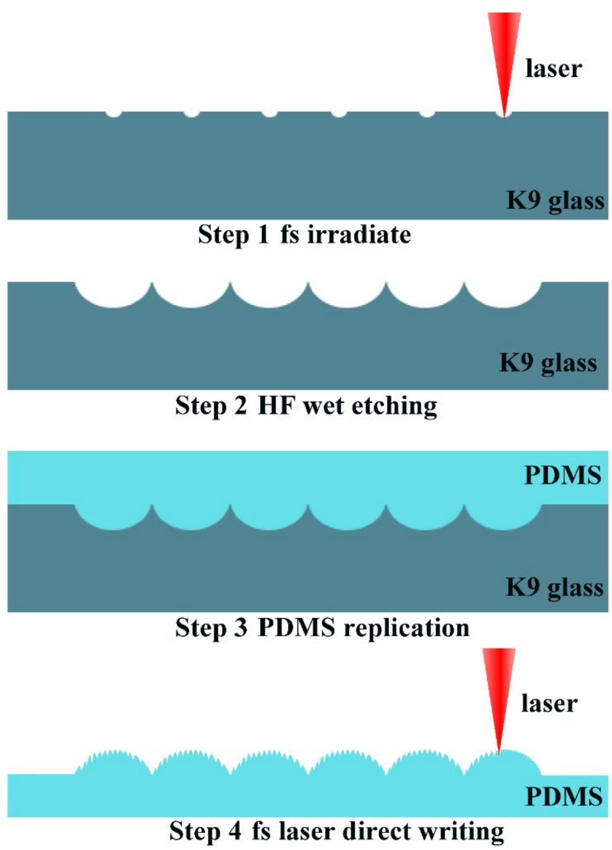

Figure 1. The schematic illustration of the fabrication process.

2.2 Sample Characterization

The morphology and three-dimensional (3D) profiles of the fabricated sample was observed by a scanning electron microscope (FlexSEM1000, HITACHI, Japan) and laser confocal scanning microscope (OLS4000, Olympus, Japan), respectively. The contact angle (CA) and sliding angle (SA) of an 8 μL water droplet on the as-prepared samples were evaluated by a JC2000D contact-angle system (Powereach, China). The imaging performance was obtained by an optical microscope (Nikon, China).

2. RESULTS AND DISCUSSION

3.1 The Morphology Features of the Fabricated Sample

Figure 2a,b illustrate the feature of the fabricated MLA (AD=6 μm) which are investigated by the SEM under different magnifications. The images show that the MLA's surface quality and uniformity. Each microlens was featured with irregular rough microstructures decorating with hundreds of nanoscale lumps (Figure 2c). These nano particles play an important role in the wettability of the surface. Moreover, the 3D morphology of the profile is investigated by a laser confocal scanning microscope and the result is shown in Figure 2d. The average diameter and height of each ommatidia are 55.23 μm and 6.46 μm, respectively. The focal length (f) of the microlens can be calculated by the following equation [25]:

$$R = \frac{h^2 + r^2}{2h}, f = \frac{R}{n-1}, \tag{1}$$

where h is the sag height, r is the radius of the microlens, n is the refractive index of the material (n=1.41 for PDMS). According to the equation, f was calculated as the value of 151.8 μm.

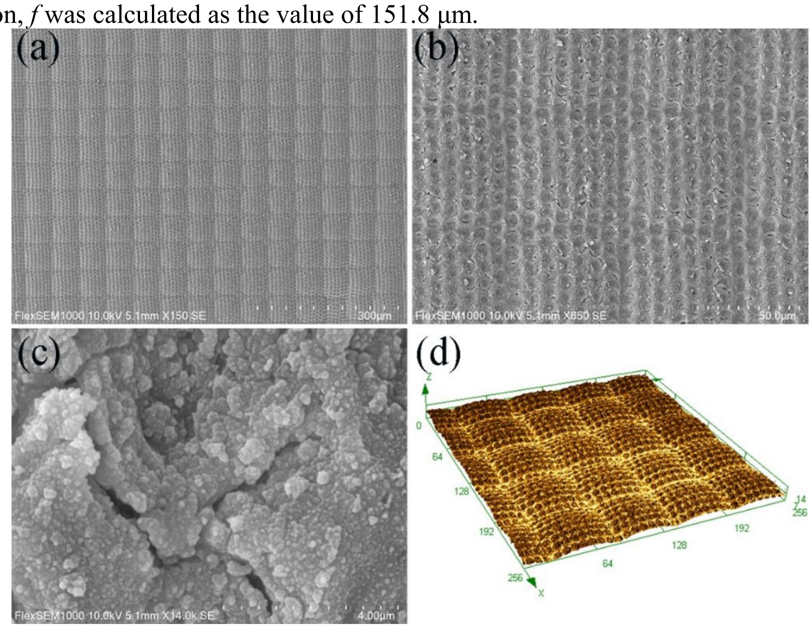

Figure 2. The 3D and 2D morphology of the fabricated MLA. (a,b) Different magnifications of the as-prepared MLA. (c) Laser induced hierarchical nano particles. (d) 3D morphology of the profile.

3.1 The Optical Performance of the Fabricated Sample

To demonstrate the optical imaging property of the as-prepared MLAs (AD = 6 μm), a normal optical imaging system consisting of a 3D movable stage, light source, an objective lens, and a CCD camera was carried out (Figure 3a). The fabricated MLAs exhibit high optical uniformity and imaging ability. As shown in Figure 3b, the clear images of letter "A" were easily captured by the objective lens and CCD camera when the letter of "A" was placed on the front of the light source. This means that the as-prepared MLAs exhibit excellent high optical imaging capability. In addition, the imaging performance of the spot light source was also investigated. When light incident on the fabricated MLAs, each of the microlens will produce a focal spot. Figure 3c shows a square array of bright spots with the same size and brightness which indicates that the as-prepared MLAs perform good consistency of the focal length.

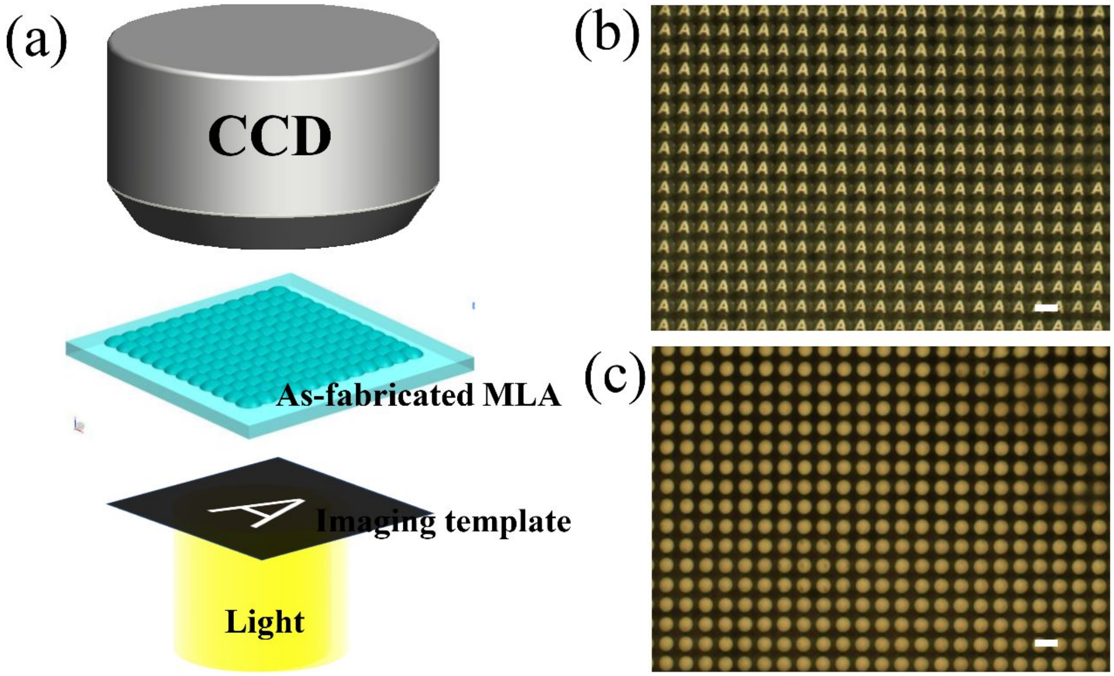

Figure 3. Optical test of the as-fabricated MLAs. (a) Schematic illustration of the optical system for the imaging test. (b,c) Imaging and focal images of the MLA. Scale bars are 50 μm.

3.2 The Superhydrophobicity of the MLAs

The static properties and dynamic behaviors of a water droplet on the normal MLA and as-fabricated MLA (AD = 6 μm) were respectively investigated and the results were exhibited in Figure 4. For the normal MLA, it exhibited a water CA of 110.5º ± 1º which was close to the intrinsic wettability of PDMS (Figure 4b). On the contrary, the water droplet almost keeps as a spherical shape on the laser-induced MLA which shows a superhydrophobicity with a CA of 158.5º ± 1º (Figure 4a). For a superhydrophobic MLA, a low SA is also necessary besides the high CA. The sliding behavior was also tested via dropping a water droplet on the surface with a tilting angle about 0.5º (Figure 4c). These properties are attributed to the large volume air trapped in the space of the rough structure that would form a layer which impedes the contact of the water droplet with the sample (the Cassie state [26]). Water in the Cassie state can easily roll away when the sample was slightly tiled. Such ultrahigh CA and ultralow SA of the as-fabricated sample endows the surface with self-cleaning ability. Dirt or the dust on the surface can be removed by the rolling water droplets.

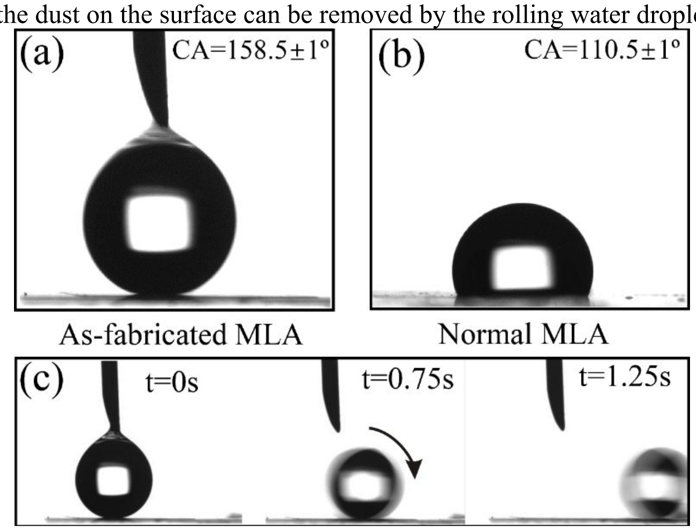

Figure 4. Wettability of the as-prepared samples. Comparison of water contact angle on the different structured MLAs surface: (a) superhydrophobic MLA and (b) normal MLA. (c) The sliding off of a 8 μL water droplet on the superhydrophobic MLA with a tilting angle of around 0.5º.

3. CONCLUSIONS

In summary, high fill factor microlens array with superhydrophobicity was demonstrated using a high-throughput method that combines femtosecond laser wet etching, PDMS replication, and laser direct writing process. The experimental results show that the MLAs, which was decorated with thousands of micro/nanoparticles, exhibits superhydrophobicity besides theirs inherit imaging ability. The microlens array can be used for optical imaging while the hierarchical micro/nano rough structures gives the sample superhydrophobicity and ultralow water adhesion. Thus, we believe that the as-fabricated MLAs will have potential applications in the solar cells, bioscience research, ocean exploration, microfluidic system, *etc*.

ACKNOWLEDGMENTS

This work is supported by the National Key Research and Development Program of China under the Grant no.2017YFB1104700, the National Science Foundation of China under the Grant nos. 51335008 and 61475124, U1630111, the Collaborative Innovation Center of Suzhou Nano Science and Technology and the International Joint Research Center for Micro/Nano Manufacturing and Measurement Technologies.

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