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Direct fabrication of microlens arrays with high numerical aperture by ink-jetting on nanotextured surface

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ABSTRACT

This work presents an economic method for fabricating solid microlens array (MLA) of high numerical aperture (NA) from UV-curable polymer by micro-droplet jetting. The prepolymer is ink-jet on a substrate with an omniphobicity enhanced by nanotexturing and octafluorobutane (C_4F_8) coating, leading to a significantly increased contact angle, therefore, an increased droplet curvature. ZnO nanopillars (NPs), which can grow economically on the substrate with a well-controlled morphology, are generated to serve the nanotexturing. Meanwhile, the ZnO NPs can effectively suppress total reflection of incidence light without introducing obviously spectral changes and directionality, which is positive for the performance of MLAs fabricated on it. Since the micro droplets can be arrayed precisely with a uniform volume, after the solidification, high quality MLAs of NA = 0.52 with smooth surface, good uniformity and reproducibility are fabricated.

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1. Introduction

Microlens and microlens array (MLA) have extensive applications in various domains, such as photolithography, imaging, communication, ranging, wide-angle light-emitting diodes [1–5]. For some applications, which require a low focal length and a high resolution, for instance, MLA with a high numerical aperture (NA) is highly desirable. However, industrialized fabrication of such a MLA remains challenging despite various techniques have been proposed to pursue a high NA. Most of these techniques or processes, such as laser ablation, photo-resist reflowing, gray-scale photolithography, molding process, involve complex processing steps or tools, leading to a poor cost-effectiveness or process reproducibility.

Micro droplet jetting on a surface, as implemented by ink-jetting [6–8], for instance, can be an economic process for directly fabricating MLA on a large area. In this process, the micro droplets of a UV-polymerizable liquid (or prepolymer) are deposited in array directly on a surface. Yet due to a typically low surface tension of the pre-polymer, it tends to be oleophilic on most planar substrate surfaces, resulting in a small contact angle, therefore a low NA for the micro droplet. Some surface treatments, such as fluorodecyltrichlorosilane (PFTS) or C_4F_8 coating, for instance, did work effectively, leading to NA = 0.41, compared with NA = 0.13 on a bare substrate [9,10]. But there is quite a limited choice of surface treatments to reduce the surface energy for a further increased contact angle of the prepolymer on a planar surface.

Since the pioneering research of Wenzel and Cassie Baxter [11,12], it has been widely known that a rough surface can behave superhydrophobic, with water droplet sitting on top of the asperities (Cassie-Baxter state) [13,14]. This leads to an overwhelming development of various surface nanotexturing techniques for generating a superhydrophobic surface for water or aqueous components which usually have a high surface tension, while omniphobicity enabled by nanotexturing have been addressed rarely in publications for liquids of low surface tension.

In this work, we demonstrate a simple and high throughput approach for fabricating MLA of high NA from a UV-curable prepolymer, by ink-jetting the prepolymer into a micro-droplet array on a nanotextured low surface energy treated substrate and which, compared to a planar surface, tends to generate an increased contact angle for the prepolymer droplets, therefore leading to an increased droplet curvature or a higher NA. Since ZnO nanopillars(NPs) can grow economically on substrate by a chemical bath-deposition process with high growth rate and adequate size

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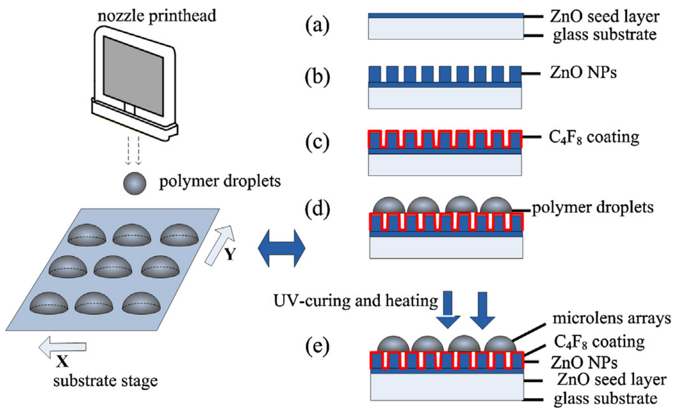

Fig. 1. Illustrative steps for fabricating MLA by micro droplet jetting. (a) Deposition of the ZnO seed layer; (b) growth of ZnO NPs; (c) C_4F_8 coating on ZnO NPs; (d) ink-jetting of prepolymer droplets; (e) UV-precuring of the prepolymer post-heating.

controllability, it is used to serve the nanotexturing. A low-energy octafluorobutane (C_4F_8) coating is done on the ZnO NPs to generate an oleophobic state for the prepolymer [15]. C_4F_8 coatings is optically transparent and will not cause any property degradation for MLAs on them.

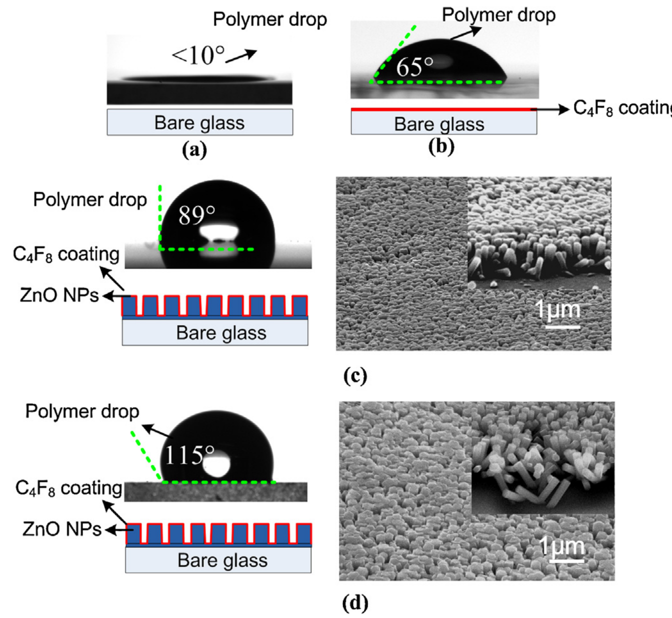

Fig. 2. Wetting conditions of prepolymer on different substrates as represented by the contact angle; (a) on bare and planar glass; (b) on C_4F_8 coated planar glass; (c) and (d) on ZnO NPs with different morphology and C_4F_8 treated glass.

2. Experimental details

Fig. 1(a)–(c) shows the two-step process for ZnO nanopillar growth. Firstly, a 30 nm thick ZnO seed layer is deposited onto a clean glass substrate using radio frequency (RF) magnetron sputter-deposition technique at room temperature (Fig. 1a). Then ZnO NPs are synthesized onto the substrate in an aqueous solution (Fig. 1b). The ZnO NP synthesis starts with dissolution of zinc nitrate hexahydrate [$Zn(NO_3)_2\cdot 6H_2O$,98%] and methenamine in deionized water with the equivalent molar concentration. Such a composite solution of zinc nitrate hexahydrate and methenamine has to be stirred vigorously at room temperature to prepare a reactive solution, into which the glass substrate with ZnO seed layer is immersed and maintained at a reaction temperature at 90 °C. The C_4F_8 coating is done in an ICP chamber by a CVD process, which uses C_4F_8 and CHF_3 gases, with a plasma fluorination time of 30 s (Fig. 1c), the

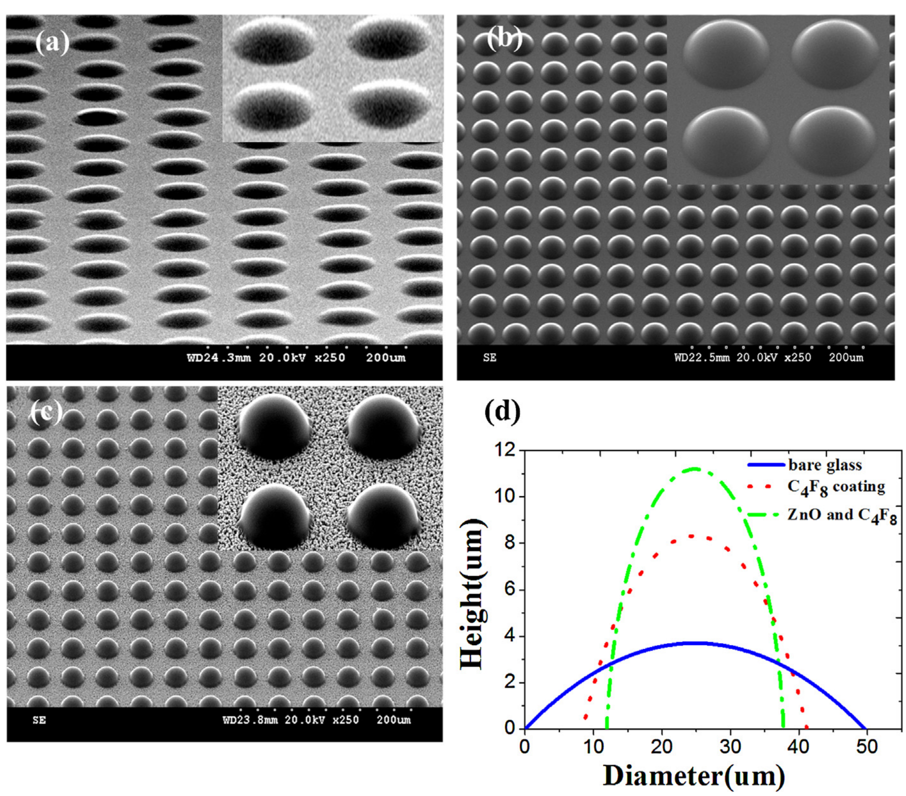

Fig. 3. SEM images of ink-jetting MLAs on different substrates. (a) On bare glass; (b) on C_4F_8 coating glass; (c) on ZnO NPs (50 mmol, 2 h) and C_4F_8 coating glass; (d) geometries of sole micro-lens measured via LSCM.

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