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Fabrication of microlens array on silicon surface using electrochemical wet stamping technique

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ABSTRACT

This paper focuses on the fabrication of microlens array (MLA) on silicon surface by taking advantage of a novel micromachining approach, the electrochemical we stamping (E-WETS). The E-WETS allows the direct imprinting of MLA on an agarose stamp into the substrate through a selective anodic dissolution process. The pre-patterned agarose stamp can direct and supply the solution preferentially on the contact area between the agarose stamp and the substrate, to which the electrochemical reaction is confined. The anodic potential vs. saturated calomel electrode is optimized and 1.5 V is chosen as the optimum value for the electrochemical polishing of p-Si. A refractive MLA on a PMMA mold is successfully transferred onto the p-Si surface. The machining deviations of the fabricated MLA from those on the mold are 0.44% in diameter and 2.1% in height respectively, and the machining rate in HF is around 1.1 μm/h. The surface roughness of the fabricated MLA is less than 12 nm owing to the electrochemical polishing process. The results demonstrate that E-WETS is a promising approach to fabricate MLA on p-Si surface with high accuracy and efficiency.

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1. Introduction

The micro/nano optic element array is widely applied in many new optical devices due to its advantages of small volume, light weight, flexible design and batch production [1]. The mirolens array (MLA) can realize a lot of unique functions that the traditional optical devices cannot. Silicon is not only an important semiconductor, but also an important material for the production of infrared lens. Silicon MLA can well improve the quality of the infrared imaging, and thus has been successfully used in the infrared optical system [2]. Moreover, the silicon MLA can realize the transition and modulation of the optical path and can be used in image sensors to process the optical image signal, therefore, it has broad application prospects [3,4].

Recently, a large number of micromachining methods have been developed for fabricating MLAs on various material surfaces, including multistep UV photolithography [5], laser direct writing [6], soft lithography [7], hot embossing [8], ultra-precision diamond turning [9], electrochemical micromachining (EMM) using nanosecond pulses [10,11], confined etchant layer technique (CELT) [12,13], reactive wet stamping (r-WETS) [14,15] and so on. But none of them can meet all the requirements of fabrication of Si MLA. For example, the lithography technique is time-consuming and the fabrication procedures are too complex [16]. The laser direct writing and the EMM method also suffer from low productivity because of their point-by-point direct way, especially when fabricating MLA on large areas [17]. The ultra-precision diamond turning and hot embossing are only suitable for the metal and the high polymer fabricatings respectively. The CELT method encounters exchange difficulty of the electrolyte with the bulk solution, which will consequently lead to nonuniform fabricated MLA within a large area [18]. The r-WETS method has a very slow Si etch rate of 2 nm/h [14], which limits its application in the fabrication of Si MLA. Therefore, it is necessary to develop a novel technique for fabricating MLA on Si surfaces in a low-cost and efficient way.

In this paper, MLA on silicon surface is fabricated by a novel micromachining approach named electrochemical wet stamping (E-WETS), which was first proposed by Zhang et al. [17] and has been applied to the electropolishing of p-Si and micromachining on Cu, Ni [19], Al [20] and GaAs [21]. The E-WETS evolves from the r-WETS method proposed by Grzybowski et al. [14,15]. In r-WETS, a patterned agarose stamp is used to confine the chemical etching to the contact area of agarose stamp and substrate. Instead of the chemical etching reaction in r-WETS, E-WETS utilizes the anodic dissolution reaction which takes place on the contact area owing to the constant supply of electrolyte from the agarose stamp

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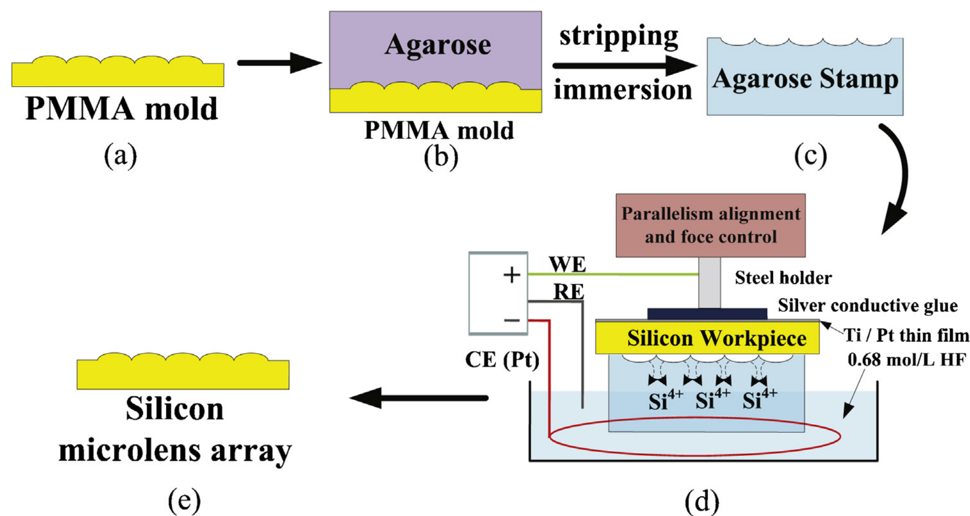

Fig. 1. Schematic illustration of the E-WETS principle and process for the fabricating of MLA on Si surface.

to the interface. Using nominal pressure to maintain the contact with substrate, the agarose stamp can progressively etch into the substrate surface, and the exactly same MLA on the mold can be fabricated on the Si surface with high efficiency.

By using E-WETS, the MLA over a large area can be fabricated in a parallel way without application of a mask on the surface. The fabrication of MLA on p-Si is actually an electrochemical polishing process, which was found by Allongue et al. [22]. They proposed that the p-Si can be polarized into electropolishing regime in HF-based solution when the potential is applied within certain range. Owing to the electrochemical polishing process, the surface roughness of the fabricated MLA can be greatly deduced. Therefore, E-WETS is a simple low-cost approach to fabricated MLA on p-Si with high-precision geometry as well as excellent surface accuracy.

2. Experimental details

The principle and process of the E-WETS are illustrated in Fig. 1. The high-strength agarose (Sangon Biotech, Biotech Grade) is employed to prepare the agarose gel stamp with desired MLA. An aqueous solution of agarose in the deionized water with weight ratios ranging from 1:8 and 1:12 is stirred and heated at 90 °C in a boiling beaker. When the agarose is fully dissolved, the boiling agarose solution is casted rapidly on a PMMA MLA mold (Center of Micronano Manufacturing Technology, Tianjin, China) which is placed at the bottom of a beaker, and then put into a vacuum chamber for 20 min to remove the air bubbles from the surface of PMMA mold. In this process shown in Fig. 1b, the agarose gel can penetrate into each micro-feature of the MLA on the PMMA mold. The PMMA MLA mold is fabricated by micro-injection molding into a nickel cavity, which is machined by ultra-precision single point diamond turning [9,23]. After the cooling of agarose gel, the agarose stamp with a negative copy of MLA on the mold is carefully stripped from the PMMA mold and then soaked in the HF etching solution (0.68 mol/L) for 2 h, as shown in Fig. 1c. Before being used, the agarose stamp should be dried on filter paper for 5 min and then placed under a stream of N_2 for 100 s to remove the remaining solution on the surface of the stamp. This step can minimize the lateral spreading of the etching solution and improve the machining accuracy.

The substrate to be etched is p-Si(100) wafer (Huajing Electronic Corporation, Wuxi, China) with 300 μm thickness, which is boron-doped and has a resistivity of 10–15 Ω cm. The backside of Si wafer is coated with a 10-nm-thick Ti film and a 50-nm-thick Pt film by sputtering to increase the conductivity of the Si wafer. Before being etched, the Si wafer is cleaned by H_2O_2, then dipped in 10% HF solution to remove the oxide layer and finally rinsed with acetone and ultrapure water. These procedures create a hydrophobic Si surface, which significantly minimizes the lateral spreading of the solution on the etching surface and improves the fidelity of the etching results.

Electrochemical micromachining of MLA on the Si substrate is performed in a homemade three-electrode electrochemical cell (Fig. 1d). The agarose stamp with feature-side up is fixed on the bottom of the electrochemical cell which is filled with HF etching solution (0.68 mol/L). The solution cannot exceed the surface of agarose stamp, i.e., only part of the agarose stamp without patterning is immersed into the solution. The Si substrate is then placed on the top of agarose stamp as the working electrode (WE). The polished surface of the Si substrate is in close contact with the agarose stamp, which ensures that the electrochemical reaction is limited to the contact areas between the stamp and the Si substrate. The backside of the Si substrate is attached to a steel holder using silver conductive glue. The precise parallelism alignment between the two surfaces of the agarose stamp and the Si substrate is adjusted by a passive orientation head, which ensures the uniformity of MLA on the Si substrate over a large area. During the machining process, the contact force between agarose stamp and Si substrate is maintained at a constant value by a force controlled system to compensate the decreasing contact force during Si dissolution. The E-WETS micromachining instrument including the passive orientation head and the force controlled system is described in our previous paper [18]. A saturated calomel electrode (SCE) and a Pt circular ring are used as the reference electrode (RE) and the counter electrode (CE), respectively. The electrochemical modulation is performed by a CHI 760D workstation (CH Instruments Co., USA). The MLAs on the PMMA mold and Si substrate are characterized using a metallographic microscope (Leica DM4000) and a confocal microscope (ZEISS Axio CSM 700).

3. Results and discussion

In order to determine the working potential for the electrochemical polishing of the Si substrate, the current-voltage curve is obtained when the electrode of Si substrate is placed on the top of agarose stamp soaked in 0.68 mol/L HF, as shown in Fig. 2. The characters of the curve replicate the current-voltage curve in the previous literatures [17,22], and the oxidation peak of current intensity occurs at the potential of 0.39 V vs. SCE as marked with a dashed line in Fig. 2. For U_{Si} < 0.39 V vs. SCE, the heterogeneous

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