SLOPING PROFILE AND PATTERN TRANSFER TO SILICON*

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This paper describes a simple and effective method to fabricate various shapes and profiles of three-dimensional (3-D) silicon microstructures, which utilizes two-step process of a 3-D lithography and dry plasma etching. The first step is to fabricate various slopes and round profiles of 3-D photoresist patterns on a silicon substrate by a shape-controllable 3-D lithography using polymer dispersed liquid crystal (PDLC) films. The second step is to transfer sloping patterns into the silicon by etching 3-D photoresist molds and the silicon surface through Inductively Coupled Plasma (ICP) process successively. The proposed fabrication method can be widely applied for silicon lens array and silicon solar cells.

1. Introduction

Recently, it is regarded as of major importance to fabricate arbitrary shapes of three-dimensional (3-D) silicon microstructures for various micro-electromechanical systems. Hence, many micromachining methods have been demonstrated for the formation 3-D silicon microstructures such as silicon microlenses, silicon solar cells, and so on. These processes can achieve angled sidewalls or surfaces in silicon through wet etching [1-2], curved surfaces in silicon by utilizing RIE lag [3], 3-D silicon structures using gray-scale lithography along with dry anisotropic etching [4], silicon solid immersion lens using reactive ion etching (RIE) with thermal photoresist reflow process [5], 3-D silicon structures including microlenses from microloading effect of RIE [6], silicon microlens mold through isotropic etching of ICP [7], microlens array for solar cells using ion beam milling with thermal photoresist reflow [8], honeycomb surface textures for multicrystalline silicon solar cells [9] .

However, these techniques have some drawbacks such as an unconventional process and a restricted shape of 3-D microstructures. Therefore, these cannot be widely applied for the formation of 3-D silicon microstructures. As the need for fabricating 3-D silicon microstructures more freely and easily, the fabrication techniques to control the profiles or shapes of 3-D silicon structures are required.

In this paper, we have introduced a simple and effective formation technique for various profiles and slopes of 3-D silicon microstructures.

2. Principles

A proposed method of sloping profile and pattern transfer to silicon consists of the following fabrication steps;

(1) A 3-D photoresist microstructure formation on a silicon substrate applying a shape-controllable 3-D lithography using polymer dispersed liquid crystal (PDLC) films [10]

(2) A 3-D pattern transfer to silicon applying Inductively Coupled Plasma (ICP) etching process

2.1. *3-D photorsist microstructure formation*

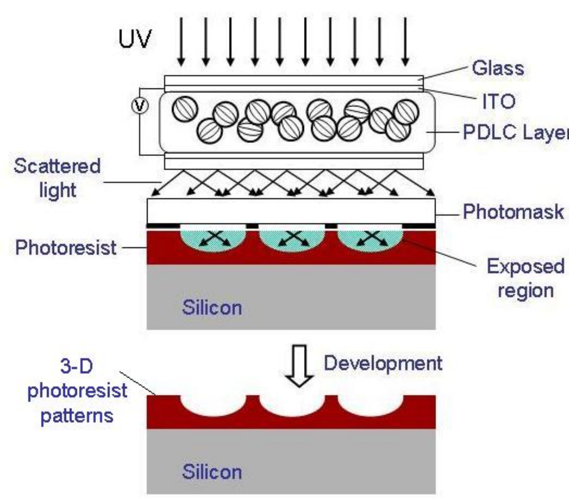

Figure 1. Schematic views showing the fabrication principles for 3-D photoresist microstructures by 3-D lithography using polymer dispersed liquid crystal (PDLC) films.

* This work was supported by Brain Korea 21 Project, The school of information technology. KAIST in 2006.

Fig. 1 illustrates schematic views of the fabrication principles for 3-D photoresist microstructures by 3-D lithography using PDLC films [10]. The only difference from conventional photolithography is the insertion of the PDLC film on a photomask, which is used as a modulating layer of ultraviolet (UV) directions incident to a thick photoresist layer. UV directions incident to photoresist molds through the PDLC film can be controlled by varying the bias voltage across the PDLC film. The photoresist layer is exposed by UV diffusing rays through the PDLC film and the photomask. By these principles, the photoresist patterns from rectangular to round cross-sections can be obtained after development process. In addition, the slopes of patterned photoresist cross-sections are regulated by the UV exposure time at each bias voltage applied the PDLC layer.

By applying this shape-controllable 3-D lithography technique, therefore, various slopes and profiles 3-D photoresist microstructures can be simply and effectively fabricated.

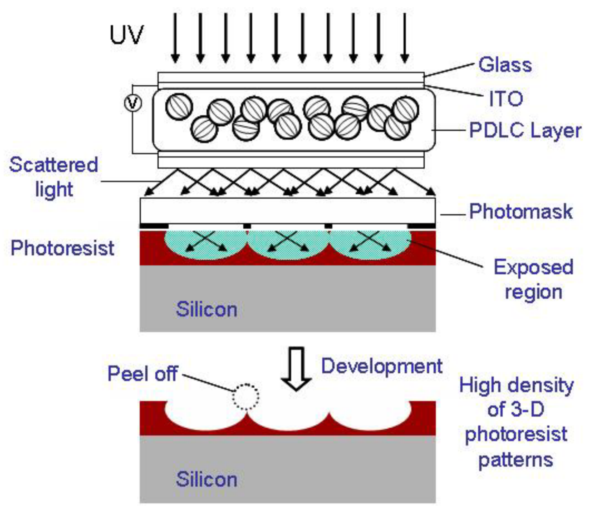

Figure 2. Schematic views showing the fabrication principles for a high density of 3-D photoresist microstructures by 3-D lithography using PDLC films.

In addition, Fig. 2 illustrates schematic views of the fabrication principles for highly dense 3-D photoresist patterns. By narrowing the spacing between the photomask patterns, the round cross-section of photoresist patterns can be overlapped, and the high density of 3-D microstructures peeled off the overlapped regions can be formed as shown in Fig. 2.

Hence, various slopes and profiles of 3-D photoresist microstructures are easily and effectively achieved by UV diffusing direction (bias voltage), exposure dose (exposure time), and photomask pattern arrangement. This 3-D lithography is very simple and useful method compatible to conventional lithography process.

2.2. *Pattern transfer to silicon*

Fig. 3 illustrates the process flows of pattern transfer to silicon for 3-D silicon microstructure fabrication. Firstly, 3-D photoresist patterns on the silicon substrate by the 3-D lithography using PDLC films are formed. Next, the 3-D photoresist molds are etched using ICP process. The photoresist molds on the silicon substrate are used as a 3-D mask in dry etching process of silicon surfaces. During ICP etching process, in the region where the photoresist molds are so thin that completely removed prior to others, the 3-D profile or shape of photoresist molds is transferred into the silicon substrate. The etching process is stopped after all the photoresist molds are fully removed.

Consequently, the pre-formed sloping profiles or shapes of 3-D photoresist microstructures are transferred into the silicon very simply. In addition, the depth or slope of 3-D silicon microstructures can be regulated by the difference in the etching rates of the photoresist and silicon of ICP process.

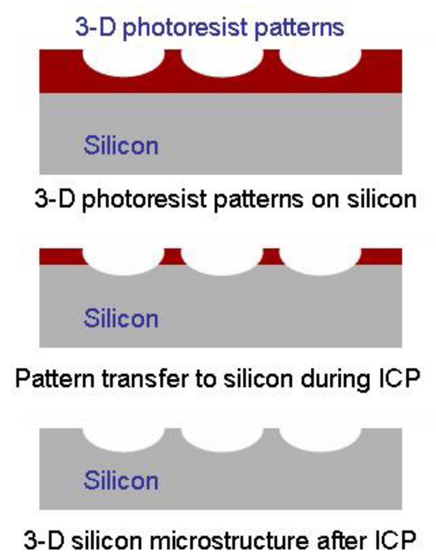

Figure 3. Process flows of pattern transfer to silicon using ICP etching process.

3. Experimental Results

3.1. *Process Conditions*

At the 3-D lithography process, thick AZ9260 photoresist film was used with spin-coating on the silicon substrate at 2000 rpm, 20 seconds for 10μm thickness. And thick photoresist layer was soft-baked at 90°C for 10 minutes. Then, the photoresist was UV-exposed through a PDLC and a photomask with varying its bias voltages and exposure times. At the ICP process in these experiments, the etching conditions used a pressure of 20mTorr, $36C_4F_8$ / $14O_2$ / 20Ar flows, a power of 1000W, a bias voltage of 100V at a process temperature of 25°C.

3.2. *Results and Discussion*

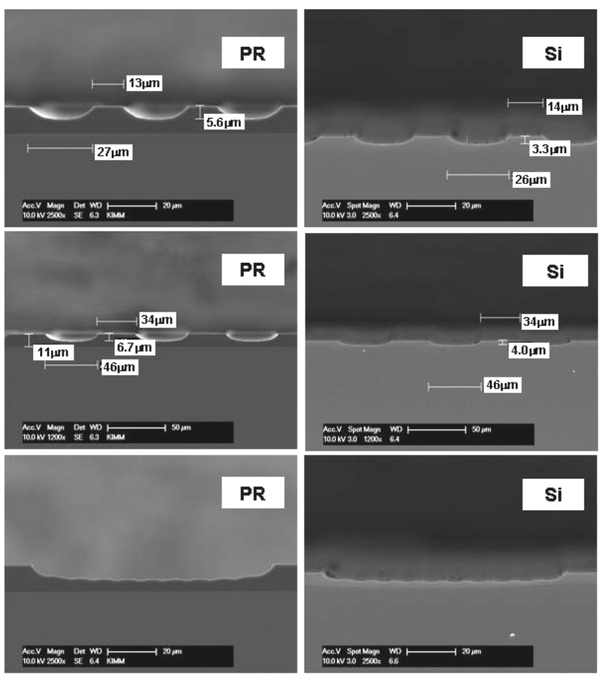

Figure 4. SEM images of cross-sections of 3-D photoresist microstructures with various sloping profiles acquired by 3-D lithography (left figures) and 3-D silicon microstructures transferred by ICP etching (right figures).

Fig. 4 shows SEM images of cross-sections of fabricated 3-D photoresist and silicon microstructures. The various profiles of 3-D photoresist microstructures as shown in left figures are fabricated by using the aforementioned 3-D lithography. From each left photoresist pattern, the 3-D silicon microstructure in its corresponding right figure is transferred by using ICP etching process. The photoresist mold is operated as an embedded 3-D mask layer during the etching process. There is no change of width in the structure during ICP process, but the depth of the final silicon structure corresponding to the original depth of the photoresist mold is designed by the relative etching ratio. Consequently, the slopes of 3-D surfaces can be controlled. From the experimental results, the etching selectivity of photoresist to silicon is ~1.7:1.

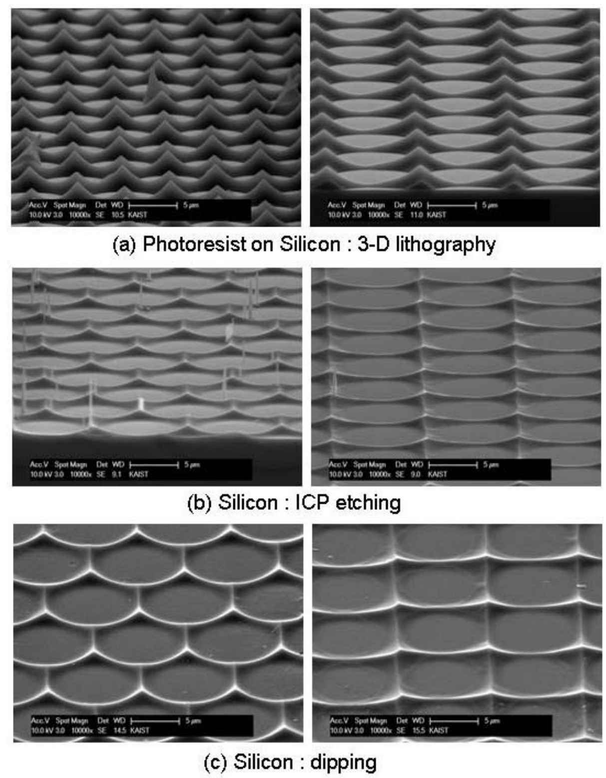

Figure 5. SEM images of (a) 3-D photoresist microstructures on a silicon substrate by 3-D lithography, (b) 3-D silicon microstructures by ICP etching process, and (c) 3-D silicon microstructures by dipping process with wet-etchant.

Fig. 5(a) shows SEM images of photoresist microstructures applying the 3-D lithography process. By narrowing the space between photomask patterns, these 3-D microstructures are densely formed. The left is UV-exposed through the photomask opening patterns of the hexagonal array, and the right is of the orthogonal array. Fig. 5(b) shows SEM images of silicon microstructures transferred from the photoresist patterns of Fig. 5(a) by applying ICP etching process. And accidental pillars of silicon surfaces are removed by dipping process of wet etchant as shown in Fig. 5(c). As a result, various sloping shapes of adjacent 3-D microstructure pattern array are achieved. These textured surfaces in silicon are widely used for the silicon microlens array and silicon solar cell.

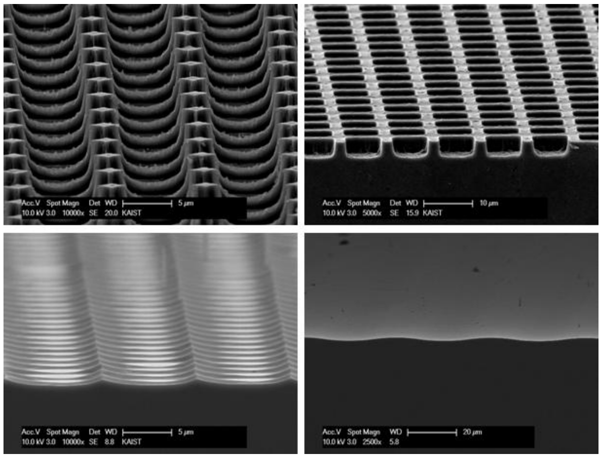

Figure 6. SEM images of various shapes or slopes of 3-D silicon microstructures.

Fig.6 shows SEM images of various slopes and shapes of 3-D silicon microstructures. According to the pre-determined sloping profiles or shapes of 3-D photoresist molds by using the shape-controllable 3-D lithography process, 3-D microstructures transferred into silicon surface are determined. These fabrication results have been shown to control the sloping profiles of 3-D silicon surface.

4. Conclusions

We have developed a new fabrication method for 3-D silicon microstructures. This method is sloping profile and pattern transfer to silicon combining the 3-D lithography using PDLC films and the ICP etching process. Applying this 3-D lithography, very different slopes and profiles of 3-D photoresist microstructure can be simply fabricated. And 3-D silicon microstructures can be transferred from these photoresist structures. This is an easy and effective method to fabricate more various slopes and profiles of 3-D silicon microstructures. This fabrication method for 3-D silicon microstructures can be utilized wide applications such as silicon microlens array, and silicon solar cells with textured surfaces.

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