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Multi-step etching of three-dimensional sub-millimeter curved silicon microstructures with in-plane principal axis

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ABSTRACT

We report a micromachining method for batch fabrication of three-dimensional curved microstructures exhibiting in-plane principal axis with respect to the wafer substrate. The target profile in the out-of-plane direction is controlled by a multi-step technique involving etching and protection alternatively with pre-designed timing of each step. The versatility of the method is studied theoretically and found to be suitable for curved microstructure realization with height-to-radius-of-curvature ratios in the order of 0.25 to 1. The method is applied experimentally on silicon substrates and an inductively coupled plasma reactor is used to carry out the multiple steps of etching and protection without human interruption. Three-dimensional curved microstructures with sub-millimeter radii of curvature are successfully demonstrated.

1. Introduction

Three-dimensional microstructure fabrication has been an intensive subject of research and development since the beginning of the last two decades. This was driven by the ever growing needs of optical, fluidic and mechanical microsystems. A large number of methods dedicated to this subject were reported in the literature with a special focus on glass and silicon substrates. The most commonly reported methods can be divided into two main categories: (i) production of three-dimensional curved microstructures on the substrate top surface; and (ii) formation of three-dimensional microstructures into the substrate volume. On one hand, advanced techniques for three-dimensional microstructure batch-fabrication on the top of silicon substrates were extensively reported. The main methods are stereo lithography [1], grayscale lithography [2–4], the MEMSNAS process and similar methods based on the lag effect in reactive ion etching [5–6], doping and subsequent selective etching [7], photoresist thermal reflow [8–9] and deposition through spatially spaced apertures [10]. On the other hand, work-piece microfabrication methods based on localized etching or deposition were also reported. This is usually carried out by mechanical scanning over the work piece area and using focused laser/electron beam [11,17–18] or miniaturized electrical/ultrasonic tips [12–16]. In all the work mentioned previously, the fabricated three-dimensional microstructures reside on the vicinity of the substrate top surface and have their principal axes oriented in the out-of-plane direction as shown in Fig. 1(a). In this article, the principal axis refers to the line passing through the vertex of the curved surface and through the center of curvature of the surface. Having the principal axes oriented in the out-of-plane direction is, however, not compatible with the need of having the principal axis oriented in-plane with respect to the substrate usually required in photonics, micro-fluidics and lab-on-chip microsystems [19–22].

Multi-step etching was reported in the literature for many purposes. For instance, it was used for improving the anisotropy of etched trenches [23], overcoming step coverage issues in metallization [24] and releasing single-crystalline MEMS structures [25]. It was also reported for the production of micro needles [26], etching a series of micro notches [27–28] and embedding cylindrical micro-fluidic channels within a substrate [21]. In these methods, the fabrication technique was either targeting a certain processing need or a specific three-dimensional microstructure and, thus, not verstaile enough for producing three-dimensional microstructures of arbitrary curved profiles. More recently, curved three-dimensional silicon microstructures were reported based on focused high-energy proton beam irradiation followed by electrochemical anodization [29] and based on hydrogen-assisted reactive ion etching [30]. However, the scale of dimensions was limited to a

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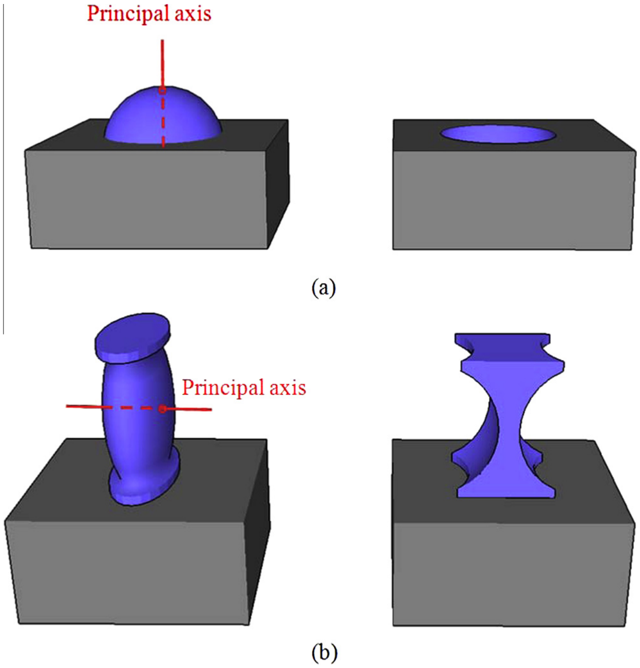

Fig. 1. Three-dimensional curved microstructures having convex (left) and concave (right) profiles. The principal axis is out-of-plane in (a) and in-plane in (b).

few tens of micrometers and the curved surface profiles were not precisely controlled.

In this work, we present a novel batch-processing multi-step technique for the production of three-dimensional microstructures overcoming the orientation challenge existing in the reported methods [31]. The technique is capable of achieving true three-dimensional shapes using two main steps: first a standard lithography to define the in-plane profile and, second a series of multi-step time-controlled etching and protection sub-steps to define the targeted out-of-plane profile. The achievable structures can have a wide range of profiles including curved profiles with concave or convex curvature. The result is three-dimensional microstructures with their principal axes oriented in-plane with respect to the substrate as shown in Fig. 1(b). The technique is applied on silicon substrates using the standard deep reactive ion etching technology. The technique is versatile enough to produce microstructures with a scale of dimensions in the order of hundreds of micrometers.

2. Multi-step etching principle

The fabrication method involves the use of a series of etching and protection steps to create the desired profile in the z-direction while the 2-D etching mask, created by standard lithography, controls the cross section in the x–y plane. For illustration, consider the cross sections drawn in Fig. 2 and the fabrication flow chart in Fig. 3(a). First, an isotropic etching is used to achieve the desired lateral etching under the mask. The imaginary cross sectional etching circle created by the isotropic etching has a radius of curvature R_1, which is equal to the desired lateral etching extent. The starting step can be either isotropic or anisotropic etching depending on the targeted profile. For the starting convex profile shown in Fig. 2, the first step should be isotropic etching. During isotropic etching, both lateral and vertical etching takes place and controlled by the etching time. The vertical etching advances the etching deeper automatically. If the resulting depth is not enough, an anisotropic etching step can be carried out in order to reach the required depth for the next lateral etching step. Then, the etched surface has to be protected from any further etching during the next cycles. A passivation step is applied to achieve the required sidewall protection. This protection step is important to prevent interaction between the multiple etching steps. The surface protection layer has to be removed from the bottom to avoid blocking of the etching. The second cycle starts by another isotropic etching step and so on… Note that the protection layer on the side walls resides in the shadow region under the etching mask and, thus, protected from any anisotropic etching step, when the latter is needed. When the targeted profile and depth are achieved, the accumulated passivation layer is removed in a surface cleaning step. The resulting surface will be rough due to the cyclic nature of the process. Therefore, a final surface smoothing step is needed to obtain a surface of better quality as shown in Fig. 2.

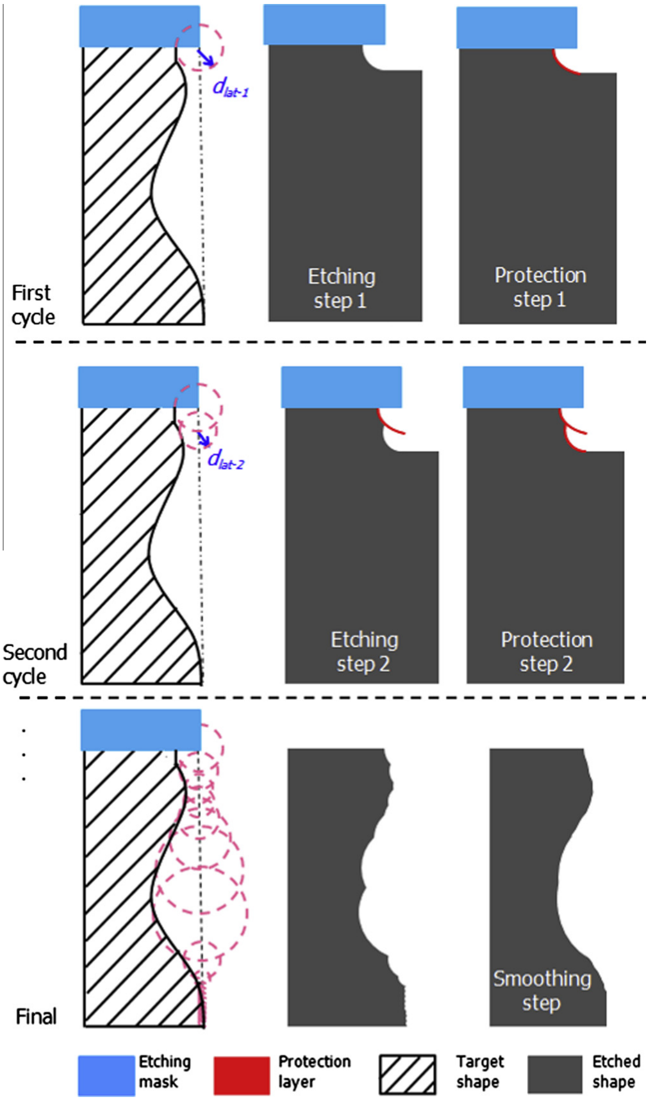

Fig. 2. Multi-step etching and protection for achieving a given profile in the out-of-plane direction. Protection layer cleaning and surface smoothing are applied after etching completion.

The isotropic and anisotropic etching times are calculated by the algorithm shown in Fig. 3(b). For each cycle, the isotropic etching process is assumed to result in equal penetration in all directions, which is denoted by d_{lat}. For instance, the lateral etching extent at a given height is calculated by Eq. (4.1) or (4.2) for a curved surface with a spherical concave or convex profile, respectively: