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Design of bulk micromachined suspensions

Weileun Fang

Power Mechanical Engineering Department, National Tsing Hua University, Hsinchu, Taiwan

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Abstract. Microsuspensions are very useful mechanical structures in microelectromechanical systems. The fabrication processes of microsuspensions, including front-side etching and back-side etching processes, have been studied extensively. Due to the restriction of the undercutting process, the front-side etching approach offers only limited patterns of microsuspension. The present study intends to develop a method to predict the possibility of fabricating microsuspensions on a (100) substrate through the front-side etching process. Microsuspensions with arbitrary shapes can be designed easily according to the proposed method. It is found that the formation of the microsuspensions predicted by the proposed technique agrees well with the experimental observation.

The contribution of this paper is to provide a convenient tool to design microsuspensions fabricated through the front-side etching process. The application of the front-side etching process on microsuspensions will become more attractive. Thus the problems of having a large cavity on the substrate, longer etching time and larger die size caused by the back-side etching process can be prevented.

1. Introduction

Microelectromechanical systems (MEMS) are the integration of the electronic circuits and the mechanical components through IC fabrication processes. The design rules and fabrication processes of the electronic circuits have been well established due to the development of semiconductor technology in the past four decades. The capability of fabricating mechanical components of MEMS devices has also been improved in the past fifteen years. At present, surface and bulk micromachining are two existing silicon fabrication technologies used to make mechanical components [1]. Both of these two technologies are developed from the standard semiconductor fabrication processes. However, the flexibility in making the mechanical components of the MEMS devices is still limited by the fabrication processes, especially for the bulk micromachining technology.

The MEMS devices fabricated through the bulk micromachining technology are constructed by several basic mechanical structures such as cavities, grooves, holes, membranes and suspensions [2]. In this paper the discussion will be focused on the fabrication of bulk microsuspensions on a (100) substrate by the anisotropic etching process. Due to the fabrication processes, most of the mechanical structures are considered to be located inside a rectangular unit for the (100) substrate. As shown in figures 1 and 2, each of the microsuspension mask patterns is inside a rectangular opening. The four sides of the rectangular opening are along $\langle 110\rangle$ directions. The fabrication processes and the applications of these basic mechanical components have been studied extensively [2]. In the present study, the microsuspensions are classified into microcantilevers and microbridges. As illustrated in figure 1, there are various types of microcantilever. It is obtained that the microcantilevers are fixed to only one side of the rectangular opening. However, these microcantilevers still have one free end. On the other hand, there are various types of microbridge shown in figure 2. It is obtained that the microbridges have more than one end fixed to different sides of the rectangular opening.

Presently, the back-side etch (BE) process illustrated in figure 3(b) is a common approach in fabricating bulk micromachined suspensions with complicated shapes [3, 4]. The primary advantage of this approach is that it offers more options on the shape of microsuspensions. However a large cavity as shown in figure 1(b) will be generated on the back side of the wafer. Therefore, the stiffness of the substrate is reduced and a large amount of the wafer is wasted. The front-side etch (FE) process as sketched in figure 3(c) is another approach in fabricating microsuspensions. Through the FE process, the problem of having a large cavity on the substrate can be avoided. Although the FE process has several advantages over the BE process, the shape of the microsuspension is restricted by the fabrication processes. The design and fabrication processes for microsuspensions and microbridges with simple shapes have been discussed [2, 5]. Due to the contribution of these studies, the bulk micromachined

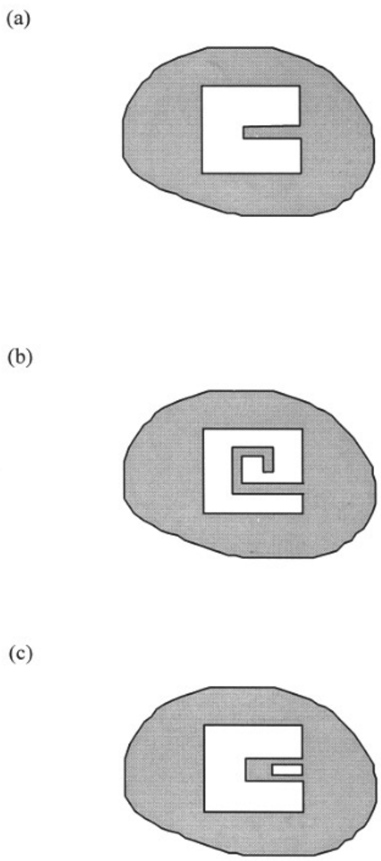


Figure 1. Mask patterns of microcantilevers with three different designs.

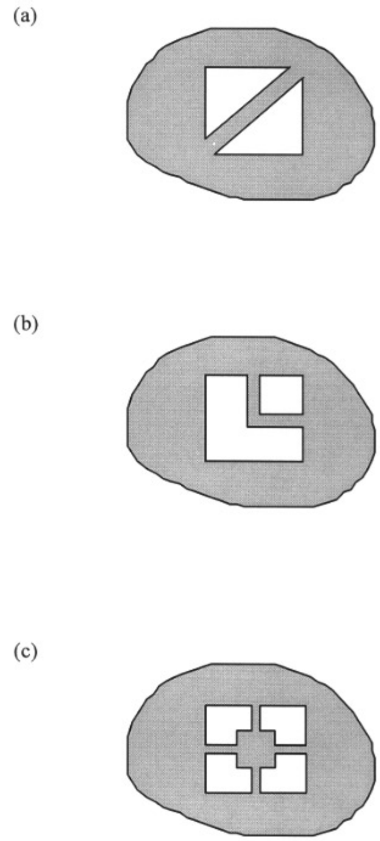


Figure 2. Mask patterns of microbridges with three different designs.

suspensions are exploited widely in many applications such as accelerometers [6], gas flow sensors [7], thermal sensors [8] and microfluidic components [9]. Unfortunately, information regarding the fabrication of microsuspensions with complicated shapes such as gimbals [10] through the FE process is still not available. This paper intends to develop a general design rule in determining the possibility of fabricating a bulk micromachined suspension through FE processes. Several mask patterns are used in the experimental work to demonstrate the proposed design rule.

2. Etching mechanism

Anisotropic etching is an important fabrication process for bulk micromachining. For anisotropic etching on a (100) single crystal silicon substrate, there are two well known characteristics: (1) the etching rate will be slowed down by {111} crystal planes, and (2) the convex corner undercutting phenomenon. A pyramidal cavity is formed with the side walls being the slow-etching {111} crystal planes when the rectangular opening on a (100) silicon substrate as shown in figure 4(a) is anisotropically etched [2]. The size of the cavity is determined by the rectangular opening on the mask pattern. The edges of the rectangular opening are aligned in the ⟨110⟩ directions. A more general observation arrived at by Pugacz-Muraszkiewicz is that the opening with arbitrary shape on a mask as shown in figure 4(b) will also form a pyramidal cavity for a sufficient etching time [11]. As illustrated by the dashed line in figure 4(b), the opening will be perfectly inscribed in this pyramidal cavity after anisotropic etching. In other words, the etching rate will not be reduced by {111} planes until the pyramidal cavity is formed. The mask pattern shown in figure 4(c) also contains one opening with arbitrary shape. In this case, the substrate under the mask pattern can be removed by convex corner undercutting. A microcantilever is obtained after a pyramidal cavity on the substrate is formed.

Based on the above discussion, the microsuspensions shown in figures 1 and 2 that are fabricated by anisotropic etching are usually located inside a rectangular domain. This rectangular domain is named the primary rectangular domain (PRD) in the following. Depicted by the dashed line in figures 5(a), 6(a) and 7(a) are the PRDs for these mask patterns. There are two groups of patterns inside the PRD: one is the pattern to define the microsuspension; the other is the pattern to define the openings. The opening is the area that is exposed to the etching solution at the beginning of the etching process. In figure 5(a), the area in light gray is the pattern for a microbridge and the areas in white are the regions for openings. Microcantilevers with any different kinds of design can be fabricated through the FE process by convex corner undercutting. For most of the microcantilever mask patterns, the undercutting process is initiated from their free end. However, it is difficult

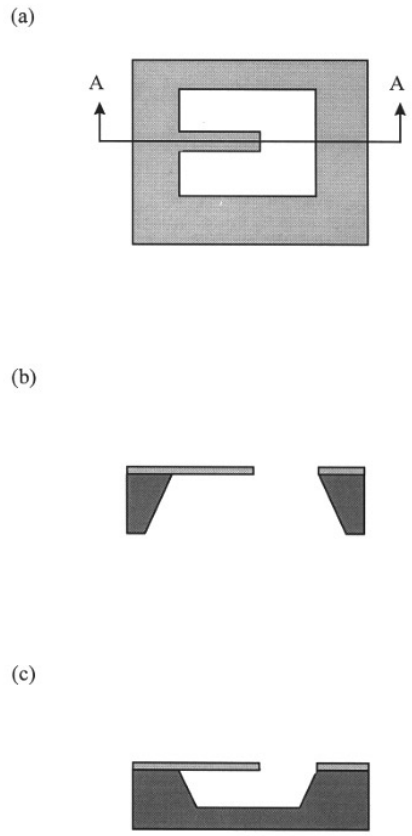


Figure 3. (a) Top view of a micromachined cantilever, (b) side view of the AA section for a back-side etched cantilever and (c) side view of the AA section for a front-side etched cantilever.

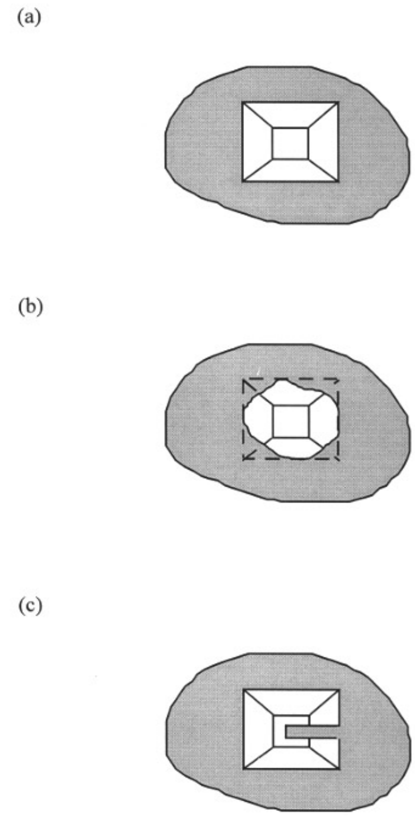


Figure 4. The pyramidal cavities of three different mask openings, (a) rectangular, (b) arbitrary and (c) cantilever.

to judge whether a microbridge mask pattern can be fully undercut by the FE process, especially when the number of openings on the microbridge mask pattern is increased. The concept proposed by Pugacz-Muraszkiewicz [11] will be exploited in developing a rule to predict the possibility of fabricating microsuspensions through the FE process.

The mask pattern shown in figure 5(a) is used to explain the proposed method. Figure 5(a) shows two rectangular openings inside the PRD. According to Pugacz-Muraszkiewicz's result [11], it is expected that two inscribed pyramidal cavities are then formed under these two triangular openings through anisotropic etching. In figure 5(b), the areas of these two pyramidal cavities are specified by the dashed lines. After the pyramidal cavities are formed, the substrate left inside the PRD is indicated by the dark gray in figure 5(c). It is obtained that the substrate remains under the mask pattern contain two convex corners. In fact, the situation shown in figure 5(c) is only an intermediate state of the entire etching process. Since the convex corners can be removed by undercutting, the etching process will be continued until the convex corner is fully etched away as shown in figure 5(d). In short, the microbridge shown in figure 5(a) can be successfully fabricated by front-side anisotropic etch. Therefore, the proposed method to judge the possibility of fabricating a microsuspension through front-side anisotropic etch can be summarized as follows:

(1) Specify the openings inside the PRD.

(2) Draw the inscribed pyramidal cavities for each opening and then obtain the substrate pattern left inside the PRD.

(3) Determine the possibility of undercutting for the substrate left underneath the mask pattern.

As a second example, a gimbal-type microbridge (microgimbal) as illustrated in figure 6 is discussed. The mask pattern which has four openings inside the PRD is more complicated. This microgimbal is designed to perform as a gimbal flat spring that can be used in the applications of a scanning mirror, or suspension for a hard disk recording head [10]. Following the procedures described previously, four inscribed pyramidal cavities associated with the four openings on the mask pattern are formed. The areas of these four cavities are illustrated in figure 6(b). As indicated by the dark gray in figure 6(c), the substrate (inside the PRD) left under the desired mask pattern is constituted by a mesa and two cantilevers. Since the mesa and cantilever can be removed easily by convex corner undercutting, it is concluded that the gimbal suspension shown in figure 6(a) can also be fabricated through FE.

In contrast, the mask pattern shown in figure 7(a) can not form a microbridge by undercutting. The microbridge in figure 7(a) is suspended by four straight arms, and named a typical four-arm microbridge. The mask pattern contains four rectangular openings with their edges aligned

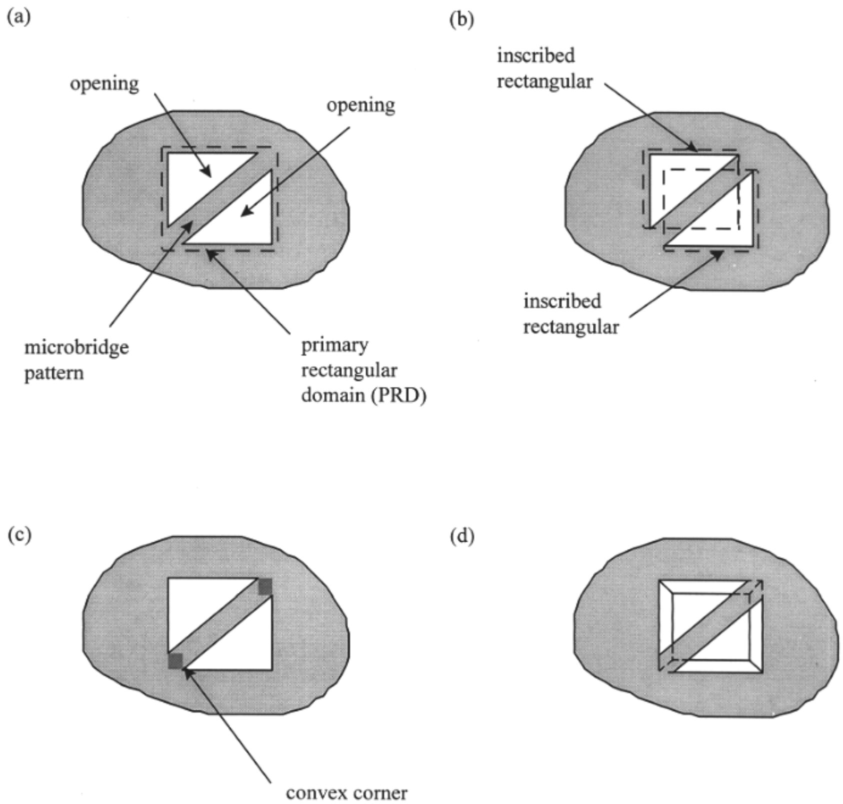


Figure 5. Mask pattern of the microbridge with two openings.

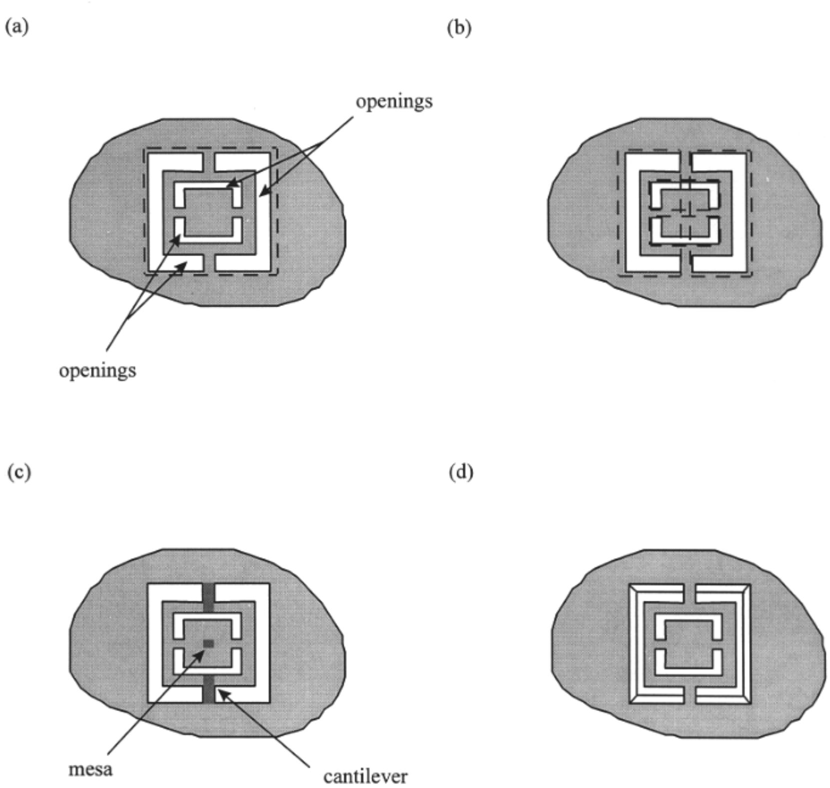


Figure 6. Mask pattern of a microbridge (gimbal flat spring) with four openings.

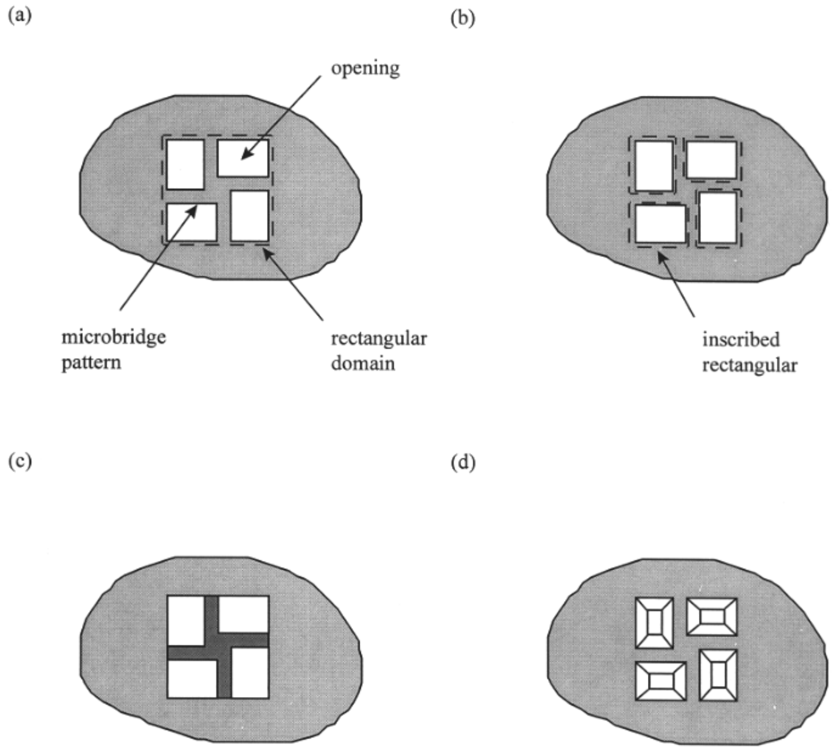


Figure 7. Mask pattern of a microbridge with four openings.

in the ⟨110⟩ directions. In this case, four inscribed pyramidal cavities as shown in figure 7(b) will be formed by anisotropic etching. However, these pyramidal cavities are isolated by the {111} crystal plane side walls. It is obtained from figure 7(b) that the PRD contains only concave corner. At this moment, the fast undercutting process enhanced by the convex corner phenomenon will be stopped. Thus, the typical four-arm microbridge defined by the mask pattern shown in figure 7(a) is difficult to fabricate by front-side anisotropic etch.

3. Experiment and results

In order to demonstrate the concept proposed in the present study, the experiment of fabricating microbridges through FE processes was conducted. Shown in figure 8 are some of the test microbridge patterns for the experiment. These test patterns consist of microcantilevers and microbridges with different number of openings. The sizes of the cavities shown in figure 8(a) are distributed from 170 μm by 150 μm to 270 μm by 210 μm. In addition, the rectangular plates of the microgimbal test patterns shown in figure 8(a) have the dimension from 50 μm by 30 μm to 150 μm by 90 μm. The rectangular plates of the microbridges shown in the bottom row of figure 8(b) are 100 μm by 100 μm. During the experiment, various thin film materials and etching solutions were used.

In the experiment, thermal SiO_2 was used as one of the materials for microbridges. A 2 μm thick SiO_2 layer was thermally grown at 1100 °C on a (100) substrate and then patterned by ion milling. SiO_2 microbridges were relieved from the substrate after the substrate was etched anisotropically with a 35% KOH solution at 85 °C. Shown in figure 9(a) is an SEM photograph of the microgimbal that contains a 50 μm by 30 μm rectangular plate shown in figure 8(a). The completed microgimbal is suspended above a pyramidal cavity with {111} sidewalls. Figure 9(b) shows the convex corner undercutting phenomenon of a microgimbal during etching. The dark gray area represents

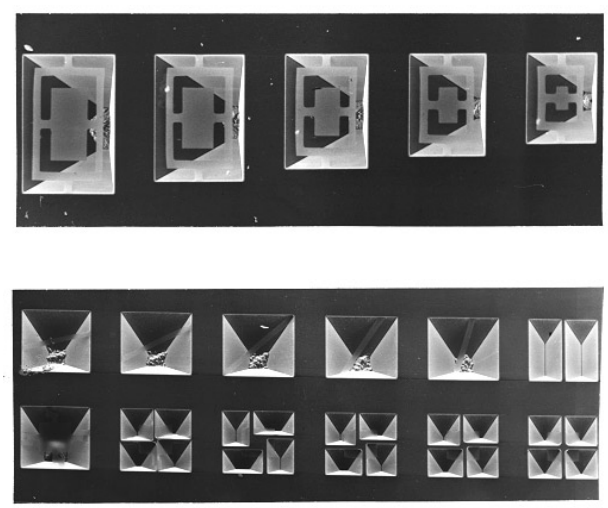
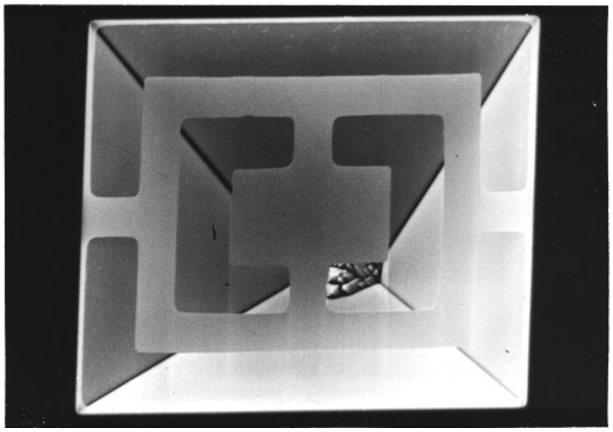
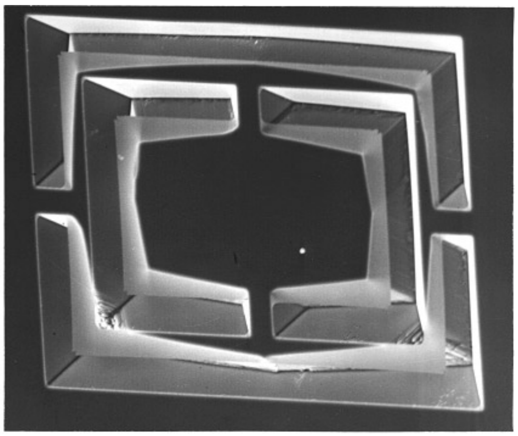


Figure 8. Some of the test mask patterns for the experiment.



(a)



(b)

Figure 9. SEM photograph showing a gimbal style microbridge when (a) fully undercut, and (b) not fully undercut yet.

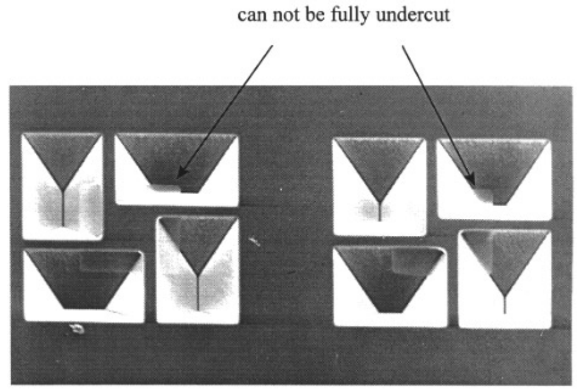


Figure 10. Mask patterns of two microsuspensions that can not be fully undercut by the FE process.

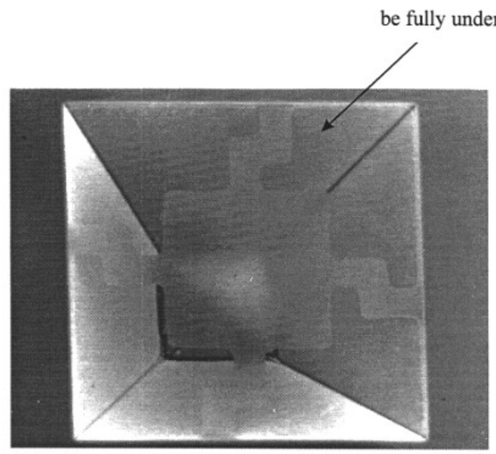


Figure 11. A modified microsuspension that can be fully undercut by the FE process.

the region where silicon substrate is still underneath the SiO_2 film. Figure 9(b) also shows that the four openings inside the rectangular domain intend to form four pyramid cavities during etching. According to the discussion in the last section, the microgimbal shown in figure 6(a) can be fully undercut. It is obtained that the undercutting mechanism predicted by the proposed method agrees very well with the experimental observation.

The microbridges were also made of multi-layer thin film materials. As shown in figure 10, there are two typical four-arm microbridges made of 0.2 μm thick PECVD nitride, 0.2 μm thick TEOS oxide and 0.3 μm thick annealed PECVD nitride. The substrate was anisotropically etched by N_2H_4 solution after patterning the thin films by reactive ion etching (RIE). In the SEM photograph of figure 10, the dark gray area represents the region where silicon substrate is still underneath the films. It is observed that both of these two four-arm microbridges have not been fully undercut yet. However the etching rate had been drastically reduced after the four pyramidal cavities were formed. Therefore, the mask patterns shown in figure 10 are difficult to relieve through the FE process. The experiment results agree well with the predicted result shown in figure 7(d).

The substrate shown in figure 8 has been etched by KOH through FE processes for 65 minutes. Apparently, all of the microgimbals in figure 8(a) have been fully undercut. In fact, it only takes about 25 min to fully undercut the smallest microgimbal. However, most of the typical four-arm microbridges in the bottom row of figure 8(b) can not be fully undercut even after more than 2 hours. If the suspensions of the typical four-arm microbridge are changed from straight type to meander type, then the etching time can be reduced remarkably. It takes less than 40 minutes to fully undercut the meander type four-arm microbridge shown in figure 11. Further, in this experiment the substrate is 500 μm thick, thus the etching time is about 6 hours if the microbridges are fabricated through BE processes. One interesting phenomenon observed in this experiment is that the undercutting process is not varying with the size of the opening. The mask patterns shown in figure 12 are 100 μm long by 15 μm wide cantilevers with three different opening sizes. It is obtained from figure 12 that the patterns of these three cases are identical during undercut when they have the same etching time, although the cavity formed during etching is different.

The microbridges were deformed by the thin film residual stresses, as indicated by the SEM photograph in

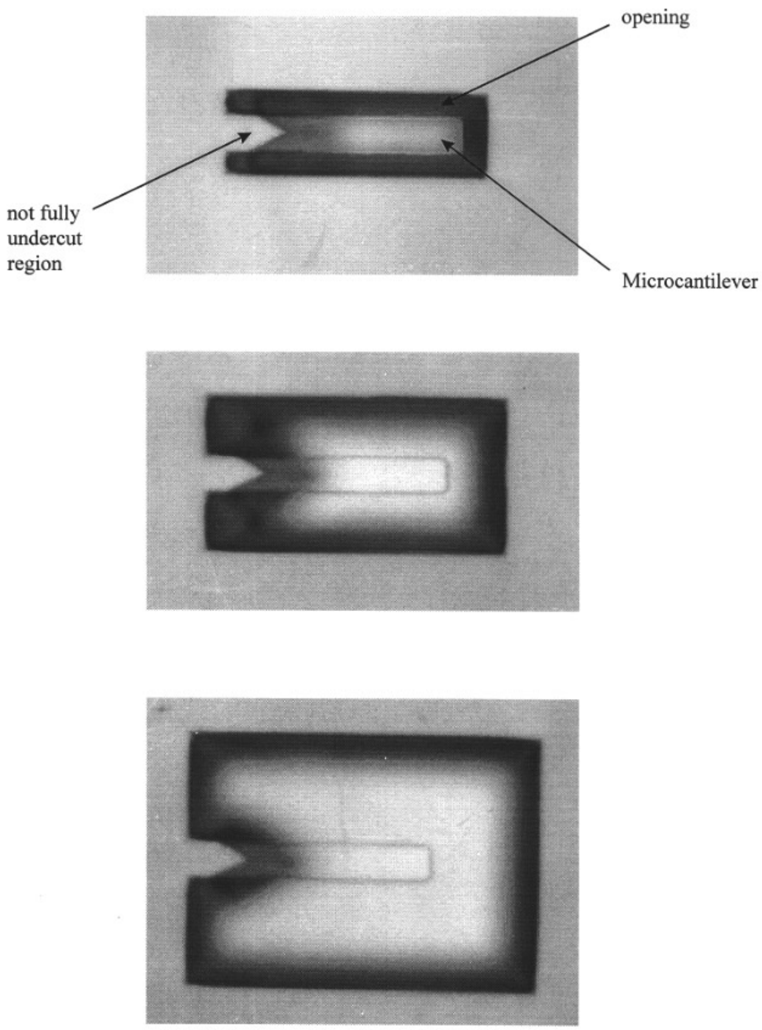


Figure 12. Undercutting of the microcantilevers with three different opening sizes for 20 minutes.

figures 8(a) and 10. The microbridge in figure 9(a) is buckled by compression thermal residual stress [12]. The full relief regions in figure 9 are warped by the total residual stresses of the thin films [13]. During the experiment, it is observed that the undercutting mechanism is not affected by the thin film residual stresses. However the residual stresses may bring up some other issues during etching. Since this article is not focusing on the stress problem, further discussion is not included here.

4. Discussion

In this paper, a method used to predict the fabricability of microsuspensions is proposed. The proposed design rule is very useful, especially when microsuspensions with complicated shape, for example, the microsuspensions shown in figures 6 and 9, are required. In addition, the proposed method can be exploited to modify the mask pattern of the microsuspension. For example, the typical four-arm microbridge shown in figure 10 can not be fully undercut through the FE process. Following the proposed design rules, the original mask pattern is modified to the meander type four-arm microbridge shown in figure 11. It is obvious that the new design of the microsuspension will be fabricated successfully through the FE process. This process has been predicted in figure 13(a). Part of the meander type four-arm suspension shown in figure 13(b) still can not be fully undercut. Hence, the substrate underneath the microbridge pattern formed four cavities. These pyramidal cavities are isolated by the {111} crystal plane side walls and the fast undercutting process enhanced by the convex corner phenomenon will be stopped. The dark gray region in figure 13(b) represents the substrate underneath the microbridge pattern which can not be removed through undercut. The result has been demonstrated through experiment as shown in figure 14.

The mask pattern discussed in figure 15 is the rotation of the mask pattern shown in the far right of the top row of figure 8(b). Figure 15(a) shows four rectangular openings inside the PRD. These openings are positioned at an angle θ with the (110) wafer flat and will form inscribed pyramidal cavities as indicated by the dashed line in figure 15(b). Thus, there are only five regions of substrate left inside the

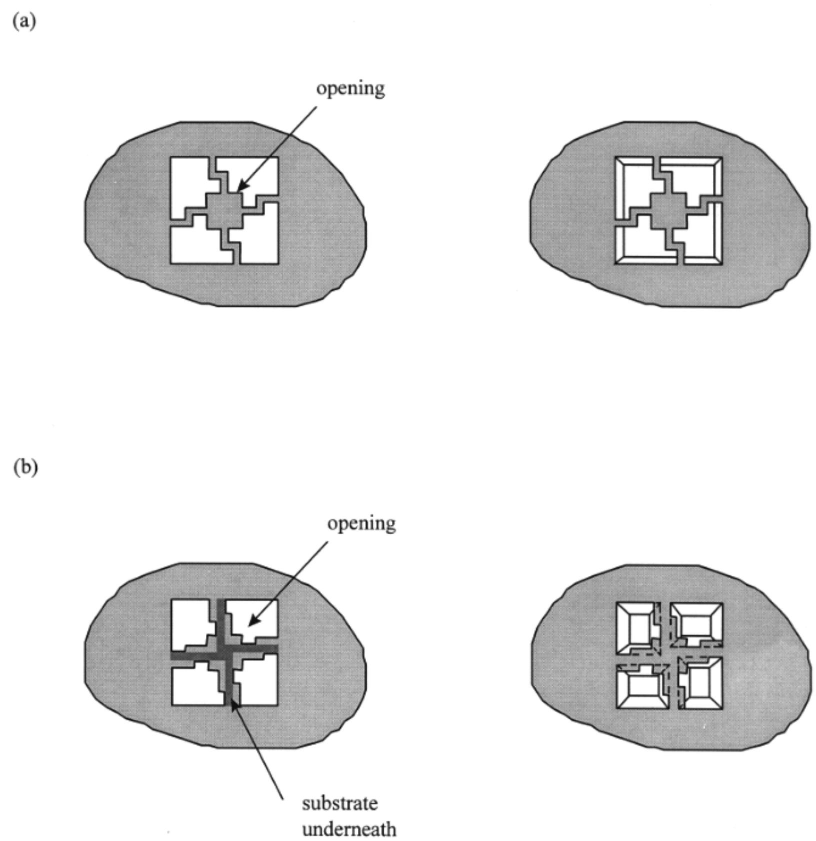


Figure 13. Meander type four-arm suspension which (a) can be fully undercut, and (b) can not be fully undercut.

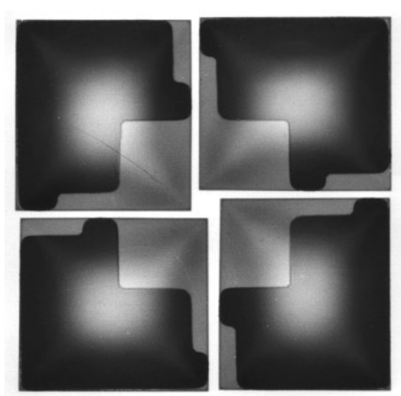


Figure 14. Experimental results for the case in figure 13(b).

PRD as shown by the dark color in figure 15(c). Since these five areas contain convex corners that can be removed by the fast undercutting process, the etching can be continued rapidly until the dark area is fully etched away as shown in figure 15(d). In addition to the modification of the mask pattern as discussed in figure 13, the rotation of the mask pattern is also an option to fully undercut microbridges. The disadvantage of this approach is that the substrate under the boundaries of the microbridge is also removed. This may change the mechanical performance, for instance stiffness and resonant frequencies, of the structure.

The thickness of the microsuspension will be reduced for both FE and BE processes. In addition, the thickness of the microsuspension made by the FE process is not uniform because of the undercutting process [2]. The variation of thickness for microsuspensions becomes obvious for a process with longer etching time or for thin film materials (or etching solution) with lower selectivity. It is difficult to predict the mechanical behaviors of the microsuspension if its thickness is not uniform. The variation of the thickness together with the residual stresses may lead to unwanted deformation of the microsuspensions. The proposed design rule provides the information regarding the possibility of fully undercutting a microsuspension mask pattern. However, it does not offer the detailed information concerning the undercutting of the substrate, for example, the fast etched planes. In other words, the proposed design rule can not be used to predict the etching time. It would be useful if the etching time of the microsuspensions were known in advance. Thus, the thickness as well as the variation of the thickness of a microsuspension after the etching process can be estimated.

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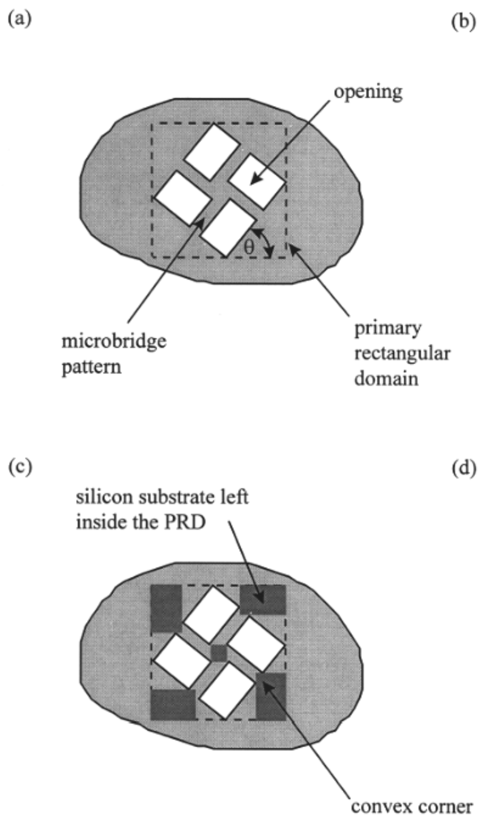

Figure 15. Mask pattern which is the rotation of the structure illustrated in figure 8(b).

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