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A vertical convex corner compensation and non {111} crystal planes protection for wet anisotropic bulk micromachining process

Huai-Yuan Chu and Weileun Fang

Power Mechanical Engineering Department, National Tsing Hua University,
Hsinchu 30043, Taiwan

E-mail: fang@pme.nthu.edu.tw

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Abstract
In general, convex corner structures and non {111} crystal planes will be undercut during wet anisotropic etching. These characteristics have been extensively exploited to fabricate freely suspended thin film structures. On the other hand, these effects have to be reduced or prevented in various applications. This study has successfully demonstrated a novel process to exploit the characteristics of DRIE to assist wet anisotropic etching. To this end, protecting structures including vertical posts and vertical walls were employed to protect convex corners and non {111} crystal planes from undercutting. In applications, the experimental results show that mesas and cavities with arbitrary shapes can be fabricated using wet anisotropic etching. Moreover, these mesas and cavities can further integrate with suspended thin film structures and the structure formed by the inclined {111} crystal planes. Hence, the variety of bulk micromachined MEMS devices will significantly increase.

1. Introduction

In addition to performing as a handling substrate, single crystal silicon wafer has frequently been used as a material for MEMS devices [1, 2]. Thus the inertia and stiffness of MEMS devices are remarkably increased. The mechanical properties of MEMS devices can also be improved. Moreover, silicon wafer has been used as a platform to integrate various optical, electrical and mechanical components. For instance, the bulk micromachined V-groove and cavity have frequently been employed to align optical components [3, 4]. Thus, high aspect ratio MEMS devices become more important regardless of the requirements of assembly or mechanical performance. In this regard, deep silicon bulk etching presently attracts much attention.

The two most common techniques for deep silicon etching are wet anisotropic etching and DRIE (deep reactive ion etching, by the BOSCH process). Wet etching is a convenient and inexpensive fabrication process. The etching rate of wet anisotropic etching is crystal plane orientation dependent. Thus, only rectangular (or square) cavities and mesas are available on a (100) substrate through wet anisotropic etching [5, 6]. Since wet anisotropic etching also has a convex corner undercut effect, a compensation pattern is often required when fabricating structures with a convex corner. On the other hand, the characteristic of convex corner undercut has been employed widely to fabricate freely suspended structures. The etching rate of DRIE is crystal plane orientation independent; in addition, DRIE has no convex corner undercut effect. Hence, DRIE can etch various kinds of cavities and mesas, for instance, rectangles, circles and triangles. However, DRIE cannot fabricate freely suspended thin film structures.

Presently, various approaches have been reported to prevent the undercut of wet anisotropic etching. For instance, compensation structures have been developed to prevent convex corner undercut [7–10]. However, these structures will occupy some in-plane spaces, especially for the case of deep silicon etching. In [11, 12], the idea of using a boron doped

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etching stop layer to prevent undercut has been employed in (111) substrate. This study has successfully demonstrated a novel process to employ the characteristics of DRIE to assist wet anisotropic etching. Thus, a wet etching technique to prevent convex corners and non {111} crystal planes from undercut becomes available. Various kinds of cavities and mesas, even circles and triangles, are available through wet anisotropic etching. Moreover, these mesas and cavities can also integrate with freely suspended thin film structures. Thus, the MEMS devices fabricated using bulk micromachining processes will significantly increase.

2. Concept and fabrication processes

In general, structures with convex corners and non {111} crystal plane sidewalls will be undercut during wet anisotropic etching. The undercut effect is directly related to the etching time as well as the etching depth. This characteristic has been extensively exploited to fabricate freely suspended thin film structures such as cantilever beams [13, 14]. On the other hand, the undercut effect has to be reduced or prevented in some applications, for instance to fabricate the proof mass of accelerometers [15]. Moreover, the shapes of structures formed by the silicon substrate are limited to the {111} crystal planes, which have the slowest etching rate. To increase the applications of bulk micromachining, it is crucial to be able to control the occurrence of convex corner undercut and to control the etching rate of non {111} crystal planes.

To this end, this study demonstrates a novel bulk micromachining process by employing DRIE to assist wet anisotropic etching. As illustrated in figure 1(*a*), this process attempts to fabricate mesas with arbitrary shapes and freely suspended structures. Briefly, mesas with arbitrary shapes are defined by DRIE, so as to prevent convex corner undercut and the crystal plane-dependent effect. Thin film protecting structures are then deposited to protect convex corners and non {111} crystal planes. As indicated in figures 1(*b*) and (*c*), these thin film protecting structures look like vertical posts (or vertical walls) anchored normal to the substrate surface. The vertical post is used to prevent the convex corner undercut and the vertical wall is employed to protect the non {111} crystal planes. In general, the protecting structure is made of etching stop layer, for instance SiO_2, Si_3N_4 or a heavily boron doped layer. This process also employs wet anisotropic etching to remove the silicon substrate, so as to fabricate V-grooves, pyramid cavities and various suspended structures. Since the sidewalls of MEMS structures formed from a silicon substrate are selectively covered with protecting thin films, those non {111} crystal planes can be protected during bulk silicon etching. Hence, circular and triangular single crystal silicon structures can survive after wet etching. The undercut will selectively occur at convex corners without protecting structures, yet freely suspended thin film structures are available through bulk silicon etching. Apparently, this approach is superior to DRIE and conventional wet anisotropic etching processes which cannot fabricate freely suspended thin film structures and mesas with arbitrary shapes simultaneously.

The typical process steps of this study are shown in figure 2. A silicon dioxide film was thermally grown and patterned on a (100) single crystal silicon wafer, as shown in figure 2(*a*). The silicon nitride deposited in figure 2(*b*) was used to act as the mask for the following thermal oxidation (in figure 2(*e*)). As shown in figures 2(*c*) and (*d*), after the photolithography of a thick photo resist, DRIE was employed to etch the thin films and silicon substrate. The height of the protecting structures was determined by the etching depth of DRIE. As shown in figures 2(*e*) and (*f*), a second silicon dioxide film was thermally grown on the substrate to form the protecting structures, and then the silicon nitride was removed. Finally, wet anisotropic bulk silicon etching was employed to fabricate V-groove and suspended structures, as shown in figure 2(*g*). During the wet etching process, the non {111} crystal planes were protected by the silicon dioxide protecting structure. It is possible to replace the silicon dioxide film with silicon nitride and heavily boron doped silicon films that have high selectivity over the silicon substrate during wet etching.

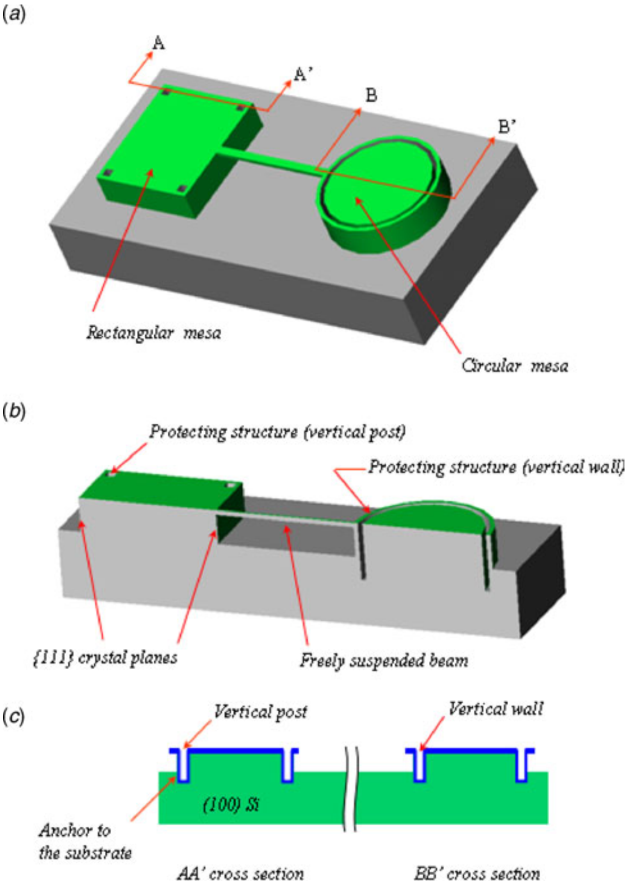

Figure 1. Schematic drawings of the structures presented in this study (*a*) a bird's eye view, (*b*) cross section of the mesa and suspended beam and (*c*) cross sections of AA′ and BB′.

3. Results

Various micromachined structures have been successfully fabricated using the process shown in figure 2 demonstrating the feasibility of this study. During the experiments, this study showed the influence of the shape as well as the location of protecting structures. The protecting structures were made of a 2 μm thick SiO_2 film, and the etching solution was a 22% TMAH at 75 °C.

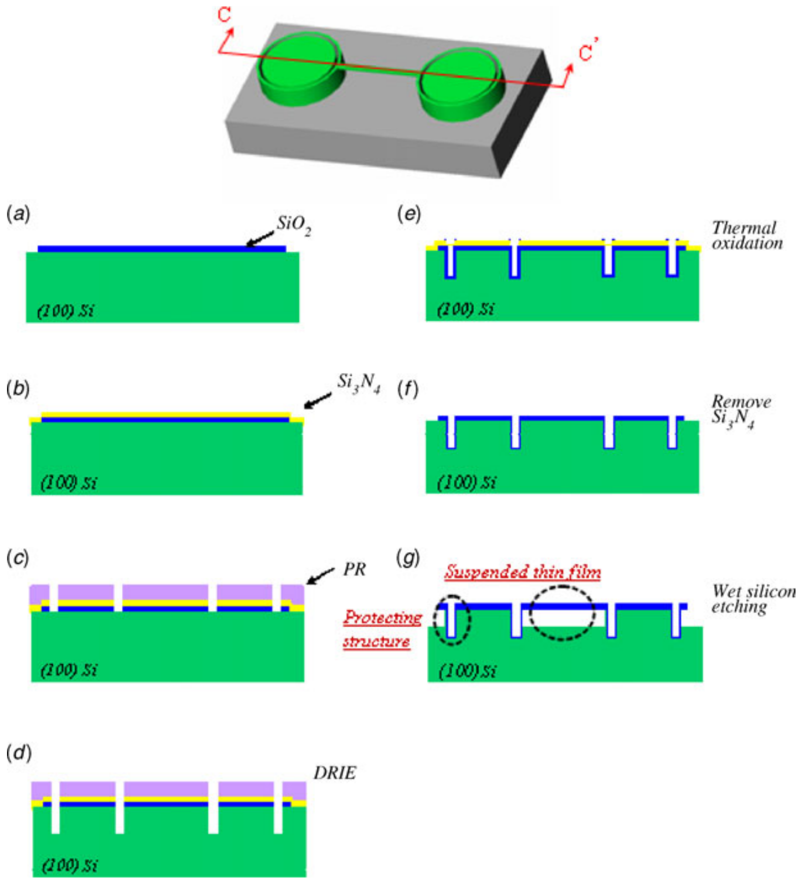

Figure 2. Flow chart of the fabrication processes.

3.1. Interior compensation mesa

The conventional approaches to prevent convex corner undercut are adding compensation structures to the corner. Hence, the spatial requirement of these compensation structures is inevitable. In some applications, there is not even enough space to add the compensation structures. The protecting structures indicated in figure 1 can be placed inside the convex corner, as shown in figure 3. The SEM photo in figure 3(*a*) shows four mesas in the shape of a cross, and each mesa has four concave corners and eight convex corners. The lower right mesa does not have any protecting structure. The lower left mesa had vertical posts, as indicated by the dashed line of the illustrations in figure 3(*a*), to act as protecting structures to prevent its convex corners from undercutting. The upper two mesas had vertical posts as well as vertical walls not only inside their corners but also inside their sidewalls. These mesas were 50 μm in height after bulk silicon etching for 2 h. Since the SiO_2 film is transparent, it is seen from the SEM photo that undercut has occurred only in the lower right mesa. The other three mesas had no undercut, although their protecting structure designs were different.

Figure 3(*b*) shows the undercut of a circular mesa as the second example. The SEM photo in figure 3(*b*) indicates that the lower right mesa has no protecting structure. The rest of the three circular mesas had different protecting structure designs inside the sidewalls. It is seen that undercutting took place along the whole sidewalls of the lower right mesa. As shown in the lower left circle, the vertical posts did prevent the mesa from undercutting. However, undercutting still took place in the other regions. Only the upper two circular mesas which had vertical posts and vertical walls along all of their sidewalls were not undercut. The protecting structures were removed after bulk silicon etching. In the experiment, the silicon mesas shown in figure 4 were obtained after the protecting SiO_2 thin film structures were etched away by BOE. It demonstrates that the convex corners and the non {111} crystal planes were properly protected by the proposed approach during wet etching.

3.2. Exterior compensation mesa

The protecting structures can also be placed outside the mesa. The mesas used in this experiment were also in the shape of a cross, as shown in the SEM photos in figures 5(*a*) and (*b*). These five mesas have four concave corners and eight convex corners. No protecting structure was added to the central mesa. The other four mesas had vertical posts outside their convex corners, but the location and pattern for the four mesas were different. The location, shape and size of these posts, as indicated by the dashed line, are illustrated in figure 5(*c*). Figures 5(*a*) and (*b*) show the results after 2 h and 4 h of bulk silicon etching, respectively. As shown in figure 5(*a*), only in the upper right mesa has undercutting not occurred. The other four mesas were more or less undercut, especially the upper

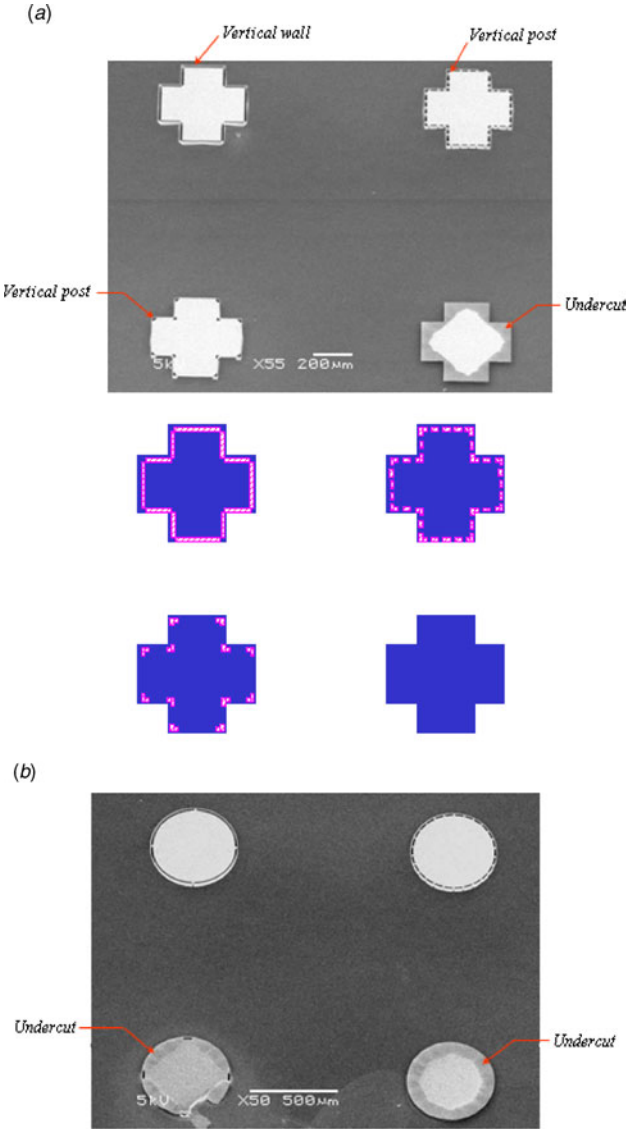

Figure 3. The undercut of (*a*) four cross shape mesas and (*b*) four circular mesas, with different interior protecting structure designs.

left and the central mesas. The undercut of the mesas can be observed more clearly in figure 5(*b*).

3.3. Cavity

In addition to mesas, protecting structures can be exploited to add variety to the shape of cavities. The SEM photo in figure 6 shows four cavities in the shape of a cross. In this case, each cavity has eight concave corners and four convex corners. The upper left cavity had no protecting structure. The upper right cavity had vertical posts inside its corners. The lower two mesas had vertical posts and vertical walls not only inside their corners but also inside their sidewalls. Briefly, the protecting structures in figure 6 are similar to the interior compensation design mentioned in section 3.1. These cavities were 50 μm deep after bulk silicon etching for 4 h. As shown in figure 6, convex corner undercut only occurred in the upper left cavity. The other three cavities had no undercut, although their protecting structure designs were different.

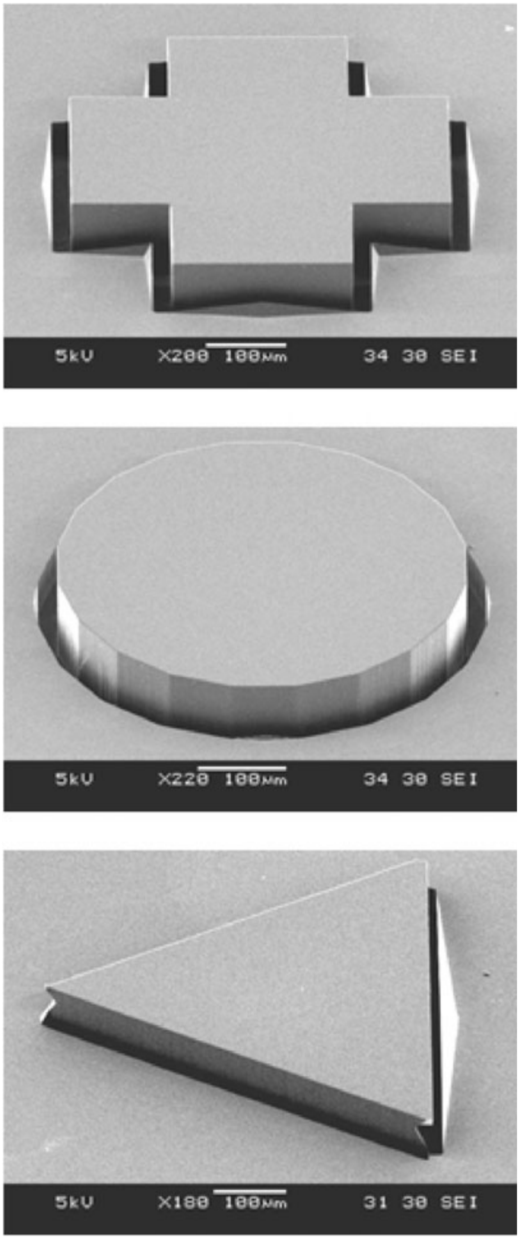

Figure 4. The cross, circular and triangular mesas were not undercut after wet anisotropic etching. The protecting structures of these three mesas were removed.

3.4. Mesa, cavity and freely suspended structure

This study employs wet anisotropic etching for bulk silicon micromachining. Hence, V-grooves, pyramid cavities and various suspended structures become available. To this end, protecting structures will be selectively placed at convex corners where undercutting is not allowed. Figure 7(*a*) shows four flat springs and two cantilevers fixed to four circular mesas. To prevent the circular mesa from undercutting, its sidewalls were all covered with a SiO_2 protecting layer. On the other hand, the cantilevers and flat springs had to be undercut for the formation of these suspended structures. There was no protecting structure on their convex corners and sidewalls. The freely suspended structures were

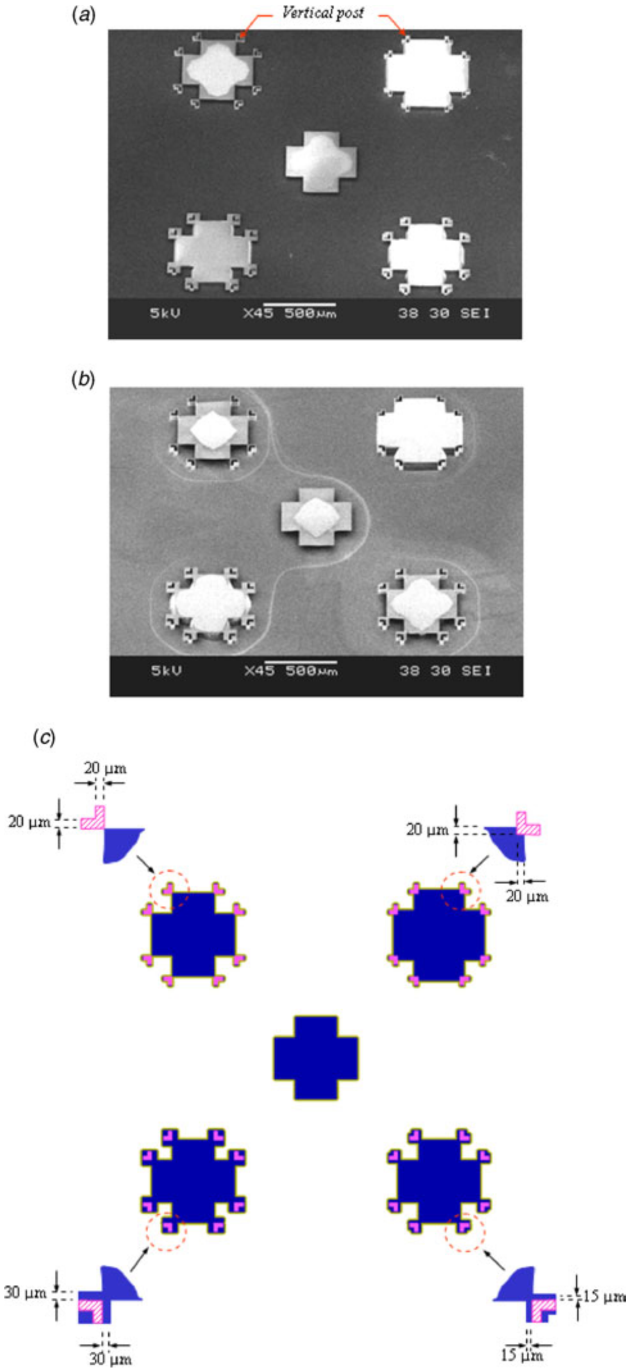

Figure 5. The undercut of four cross shape mesas with different exterior protection post designs (*a*) etching for 2 h, (*b*) etching for 4 h and (*c*) the dimensions and locations of the vertical posts.

also made of SiO_2 thin film. Figure 7(*b*) shows eight bridges and five circular mesas located inside a cavity. It can be clearly observed that the sidewalls of the cavity are formed by the {111} crystal planes. Wet anisotropic etching was employed for the formation of the suspended bridges and cavity. During wet anisotropic etching, the sidewalls of the circular mesas were protected by SiO_2 protecting thin film. In conclusion, the results in figure 7 demonstrate that the proposed process did successfully integrate various kinds of MEMS structures.

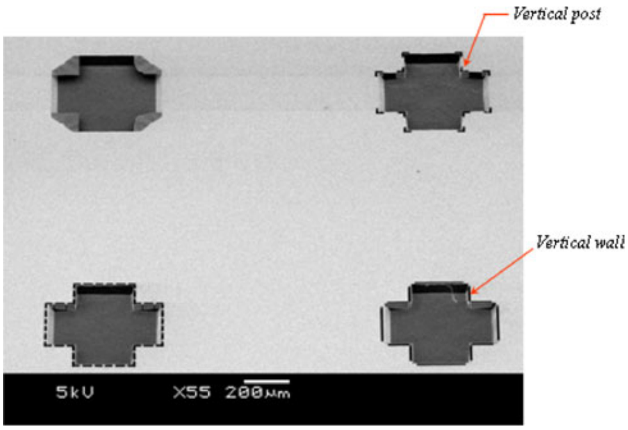

Figure 6. The undercut of four cross shape cavities with different interior protecting structure designs.

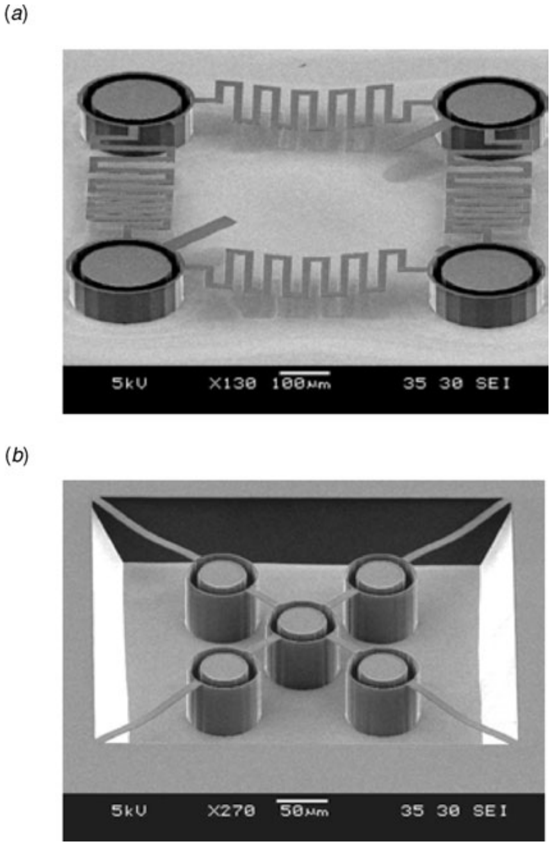

Figure 7. The integration of freely suspended beams and circular mesas after bulk silicon etching (*a*) on top of a substrate and (*b*) inside a cavity formed by {111} crystal planes.

4. Discussions and conclusions

The DRIE process is not influenced by the crystal planes, and can produce mesas and cavities in various shapes. On the other hand, wet anisotropic etching has the characteristic of convex corner undercutting, which can be exploited to fabricate suspended structures. This study has successfully demonstrated a novel process to combine the advantages of wet anisotropic etching and DRIE. The experimental results show that mesas and cavities with arbitrary shapes can be fabricated using wet anisotropic etching. Moreover, these

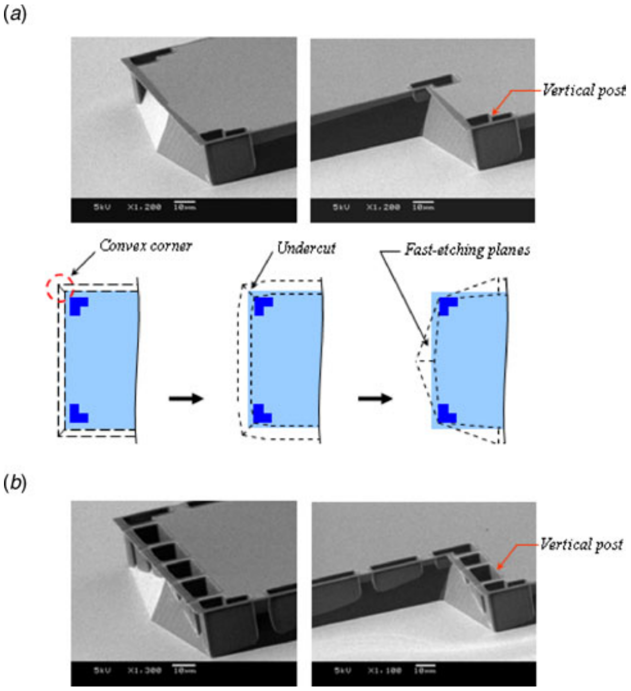

Figure 8. The close-up of the mesa in figure 3(*a*) (*a*) the lower left mesa and the variation of its sidewall crystal planes during etching and (*b*) the upper right mesa.

mesas and cavities can further integrate with suspended thin film structures and the structure formed by the inclined {111} crystal planes. Hence, the variety of bulk micromachined MEMS devices will significantly increase.

As shown in figure 3(*a*), the protecting structures were effective in preventing the convex corners from undercutting. Moreover, the three mesas had the same etching results no matter whether the sidewalls had protecting structures or not. Since the sidewalls of the cross shape mesas in figure 3(*a*) are formed by {111} crystal planes, the undercut will only occur at the convex corner. Figure 8(*a*) shows a close-up of the lower left mesa in figure 3(*a*). Figure 8(*a*) also shows the variation of the sidewall crystal planes during etching. Convex corner undercutting still occurred as illustrated in figure 8(*a*). The undercutting near the convex corners stopped once it reached the vertical posts. However, the fast-etching planes starting at the convex corner continued to propagate along the sidewalls of the mesa. Thus, the sidewall of the mesa in figure 8(*a*) was formed from two planes. In short, undercutting still occurred for the lower left mesa in figure 3(*a*) for a longer etching time, although the vertical posts were employed. Figure 8(*b*) shows the close-up of the upper right mesa in figure 3(*a*). The sidewalls of this mesa were surrounded with vertical posts. In this case, undercutting near the convex corners and the sidewalls was stopped by the vertical posts. Hence, the mesa was properly protected even for a longer etching time.

As for mesas with sidewalls not in the ⟨110⟩ direction, for instance, the circular mesa in figure 3(*b*), the {111} crystal planes will no longer be applied to stop the undercut. Hence the sidewalls of the lower right circular mesa in figure 3(*b*) were seriously undercut during wet anisotropic etching. Consequently, triangular and circular mesas have never been reported for wet anisotropic etching. In conclusion, protecting structures have to be added to sidewalls that are not {111} crystal planes. Although four vertical posts were added to the lower left mesa in figure 3(*b*), undercutting still occurred in the other regions. Figure 9(*a*) shows a close-up of the upper two mesas in figure 3(*b*). It shows that the undercut along the sidewalls of these two mesas was fully stopped by SiO_2 vertical posts and walls. Figure 9(*b*) shows two triangular mesas after wet anisotropic etching for 4 h. The left triangle had several small vertical posts on each side; however, the right triangle had a vertical wall on each side. Apparently,

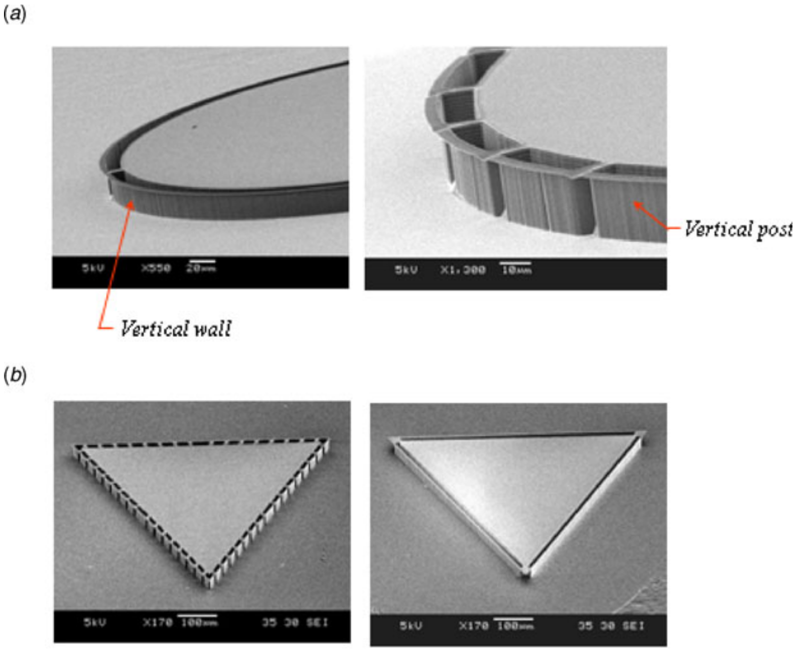

Figure 9. Demonstration of the non {111} crystal planes of two different mesas protected by SiO_2 protecting structures (*a*) circular mesa and (*b*) triangular mesa.

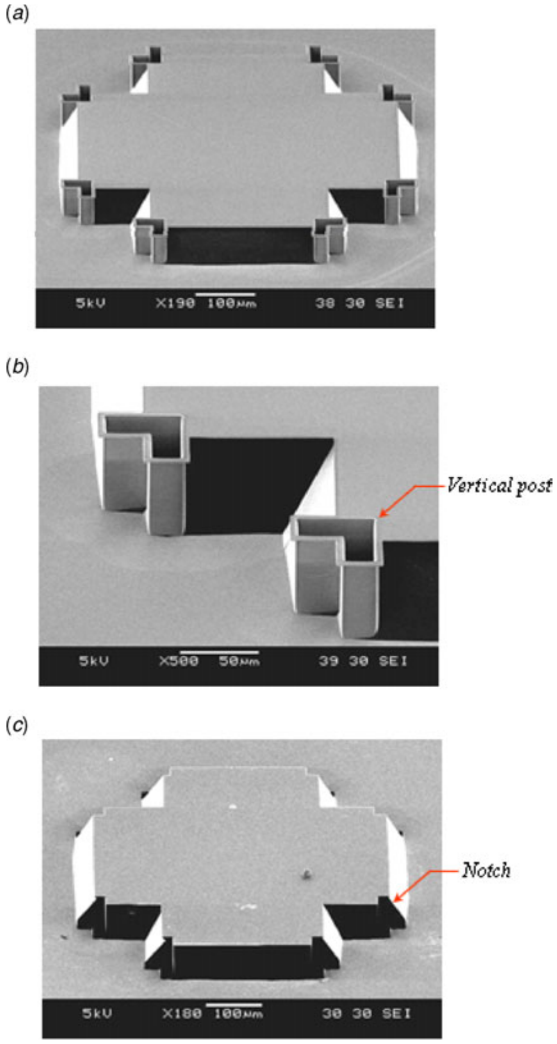

Figure 10. The close-up of the upper right mesa in figure 5 (*a*) the mesa (*b*) the convex corner with protection post and (*c*) the convex corner after the protection post was removed.

undercutting along their sidewalls was thoroughly prevented by these SiO_2 protecting structures.

The protecting structures can also be placed outside the mesa. However, convex corners will still be attacked if the protecting structures do not come in close contact with them. As shown in figure 5, only the upper right mesa, which had its convex corners overlapped with the vertical posts, was not undercut. Figures 10(*a*) and (*b*) show close-ups of the upper right mesa and its convex corner. In these photos, the SiO_2 vertical posts anchored on the substrate, are clearly observed. As shown in figure 5(*c*), these vertical posts overlap with the convex corner for only 20 μm. The results show that the convex corners are protected by these posts. Moreover, the photos also show that the sidewalls of the cross shape mesa are protected by the {111} crystal planes. As shown in figure 10(*c*), the mesa has several small notches left on its convex corners after the SiO_2 vertical posts were removed. However, the shape of the mesa is not influenced by undercutting. Since the pattern of these notches is defined by the photo mask, their size can be predicted in advance.

In addition to the SiO_2 thin film, a heavily boron (p^{++}) doped etch stop layer can also be employed as the protecting layer. A typical fabrication process is briefly illustrated in figure 11(*a*). The p^{++} protecting layer was selectively doped on suspended structures, and the SiO_2 protecting layer was selectively covered on part of sidewalls of the circular mesa. During the wet etching process, the non {111} crystal planes were protected by the SiO_2 layer. Moreover, four flat springs and two cantilevers were also prevented from etching due to the boron etch-stop effect. Finally, the protecting structures were removed after the SiO_2 thin film was etched away. The SEM photo in figure 11(*b*) shows four suspended flat springs and two suspended cantilevers fixed to four circular mesas. The structures in figure 11(*b*) are similar to those in figure 7(*a*). In this manner, the beams and bridges can be connected to the mesas directly.

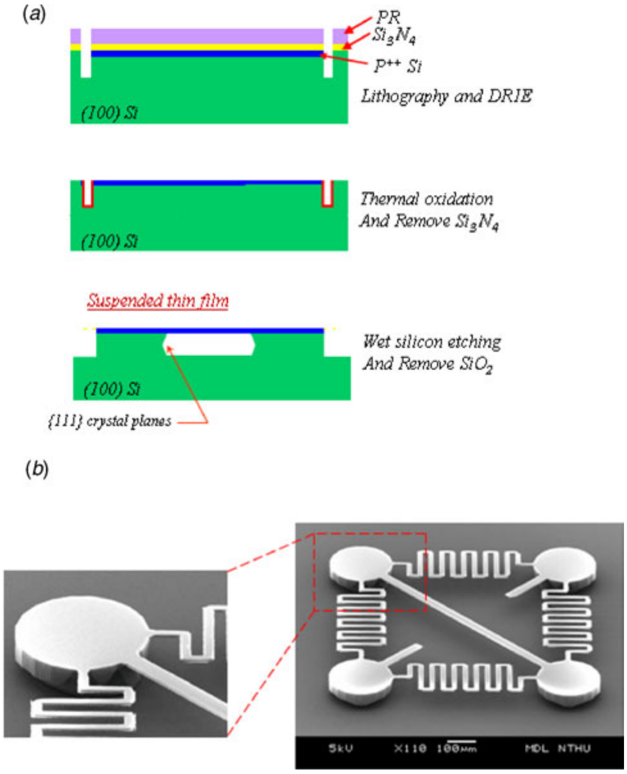

Figure 11. The integration of freely suspended heavily boron doped beams with circular mesas after bulk silicon etching.

Acknowledgments

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