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Bulk micromachining fabrication platform using the integration of DRIE and wet anisotropic etching

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Abstract This study presents a bulk micromachining fabrication platform on the (100) single crystal silicon substrate. The fabrication platform has employed the concept of vertical corner compensation structure and protecting structure to integrate the wet anisotropic etching and DRIE processes. Based on the characteristics of wet anisotropic etching and DRIE, various MEMS components are demonstrated using the bulk micromachining platform. For instance, the free suspended thin film structures and inclined structures formed by the {111} crystal planes are fabricated by the wet etching. On the other hand, the mesas and cavities with arbitrary shapes and the structures with different leve l heights (or depths) are realized by the characteristics of DRIE. Since the aforementioned structures can be fabricated and integrated using the presented fabrication platform, the applications of the bulk micromachining processes will significantly increase.

Keywords DRIE, Wet anisotropic etching, Bulk micromachining

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Introduction

Bulk silicon micromachining is regarded as one of the primary MEMS fabrication technologies. Various micromachined structures such as V-grove and cavity become available after etching the silicon substrate anisotropically [1, 2]. Moreover, the convex corner undercut effect has been extensively employed to fabricate free suspended thin film structures [3, 4]. Presently, the high aspect ratio (HARM) devices become more important in MEMS applications. For instance, the single crystal silicon wafer has also been employed as the material for MEMS devices to increase their inertia and stiffness [5, 6]. The wet anisotropic etching and DRIE (deep reactive ion etching, by BOSCH process) are the two most common techniques for deep silicon etching. However, the applications of wet anisotropic etching are limited to the crystal planes of silicon substrate and convex corner undercut effect; and the DRIE technique is unable to fabricate free suspended structures. Hence, the existing bulk silicon micromachining processes have limited available components to become a powerful fabrication platform.

The concept of using vertical corner compensation structure to prevent the undercut during wet anisotropic etching was presented in [7]. The protecting structure was also used to protect the non {111} crystal planes from etching. Hence, it is possible to employ the DRIE to assist the wet anisotropic etching to increase the variety of bulk micromachined MEMS devices. In short, under the assistant of DRIE, the 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.

This study presents a bulk micromachining fabrication platform on the (100) single crystal silicon substrate. The fabrication platform has employed the concept of vertical corner compensation structure and protecting structure in [7] to integrate the wet anisotropic etching and DRIE. Based on the characteristics of wet anisotropic etching and DRIE, various MEMS components are demonstrated using the bulk micromachining platform. For instance, the free suspended thin film structures and inclined structures formed by the {111} crystal planes are contributed by the wet etching. On the other hand, the mesas and cavities with arbitrary shapes and the structures with different level heights (or depths) are realized by the characteristics of DRIE. Since the aforementioned structures can be fabricated and integrated using the presented fabrication platform, the applications of the bulk micromachining processes will significantly increase.

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Concept and Fabrication Processes

Wet anisotropic etching is the primary process for the bulk silicon micromachining. The wet anisotropic etching has two characteristics. First, its etching rate depends on crystal plane orientation. In general, the {111} planes always have the slowest etching rate, and will form the "etching stop layer." [8, 9] Thus, the sidewalls of MEMS structures formed by the silicon substrate are limited to {111} crystal planes. Second, the convex corner structure will be undercut during the wet anisotropic etching. This characteristic has been extensively exploited to fabricate free suspended thin film structures such as cantilever beams. On the other hand, this effect has to be reduced or prevented in some applications, for instance to fabricate the proof mass of the accelerometer [10, 11]. The DRIE is another option for the anisotropic bulk silicon etching. The sidewalls of MEMS structures will be protected by the polymer deposition instead of {111} crystal planes during DRIE [12, 13]. Various MEMS structures such as circular and triangular mesas become available since their shape is no longer limited to {111} crystal planes. However, the DRIE process cannot fabricate free suspended structures since the convex corner undercut effect does not exist.

This study develops a novel bulk micromachining platform on the (100) single crystal silicon substrate using the integration of the wet anisotropic etching and the DRIE. This platform employs the characteristics of the DRIE process to prevent the convex corner undercut and crystal plane dependent effects during bulk etching. The protecting structures (or named vertical convex corner compensation) [7] are then grown or deposited to protect the convex corner and fast etching crystal planes. The mesas with even circular and triangular shapes become available after wet anisotropic etching, as shown in Fig. 1. In addition, the characteristics of the RIE lag during deep silicon etching and the {111} crystal planes are used to fabricate the stepped structures with various level depths. The undercut will selectively occur at the convex corner without protecting structures, yet free suspend thin film structures remain available through the bulk silicon etching. Thus, the characteristics of wet anisotropic etching are exploited to provide V-grooves, pyramid cavities, and various suspended structures in Fig. 1. Since all of the aforementioned structures are fabricated using the presented fabrication platform, they can be integrated on the (100) silicon substrate as shown in Fig. 1.

Figure 2 illustrates the typical process steps of this study. A silicon dioxide film was thermally grown and patterned on a (100) single crystal silicon wafer as shown in Fig. 2a. As shown in Fig. 2b, a silicon nitride was deposited to act as the mask for the following thermal oxidation in Fig. 2e. As shown in Fig. 2c, d, after the photolithography of a thick photo resist, the DRIE was employed to etch the thin films and silicon substrate. Thus, the structure with arbitrary shape was defined. The height of these structures was determined by the etching depth of DRIE. In addition, the RIE-lag was exploited to produce the stepped-structures. As shown in Fig. 2e, f, a second silicon dioxide was thermally grown on the substrate to form the protecting post, and then the silicon nitride was removed. As shown in Fig. 2g, the wet anisotropic etching was employed to fabricate inclined structures and suspended structures. During the wet etching process, the non {111} crystal planes were protected by the silicon dioxide post. It is possible to replace the silicon dioxide film with the silicon nitride and heavily boron doped silicon films that have high selectivity over silicon substrate during wet etching. Finally the vertical silicon dioxide protection was removed to form circular mesas and stepped-structures, as shown in Fig. 2h.

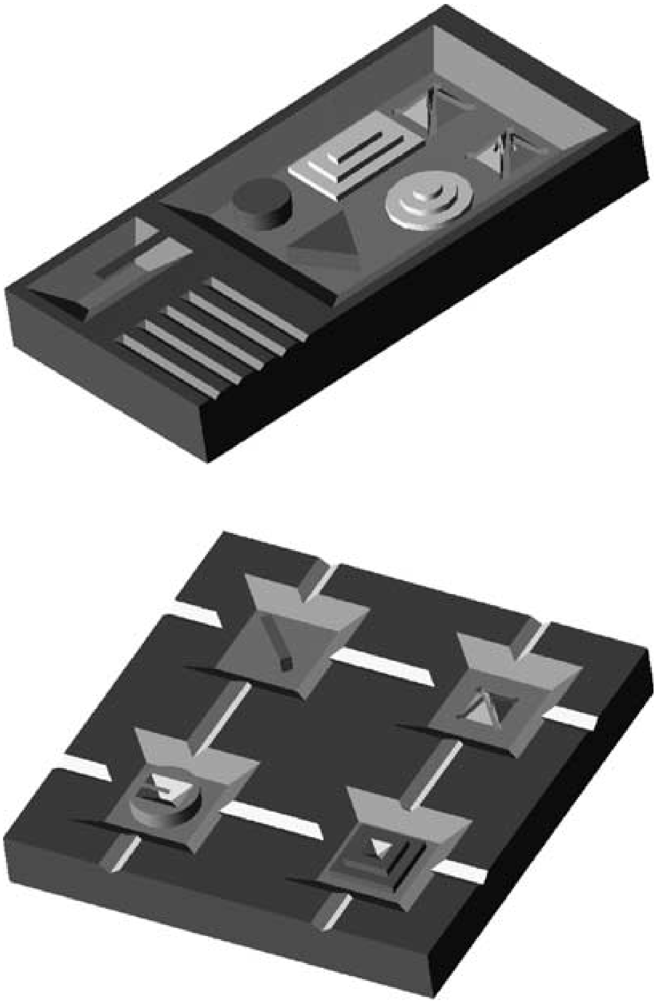

Fig. 1. Schematic drawings of the monolithically integration of the micromachined structures on the substrate

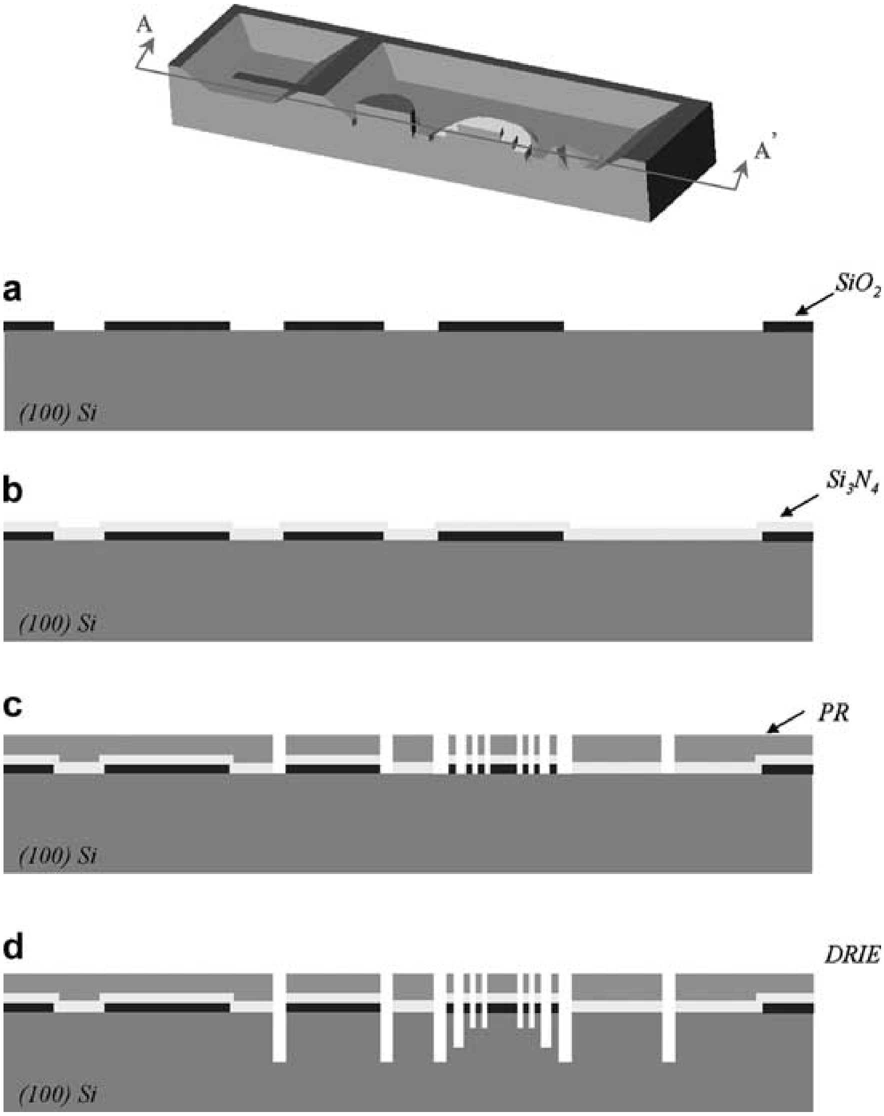

Fig. 2. Flow chart of the fabrication process

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Results

To demonstrate the feasibility of the fabrication platform, the structures illustrated in Fig. 1 have been successfully fabricated using the process in Fig. 2. This study showed not only the fabrication results of each structure but also the integration of these structures. The protecting structure employed in this experiment was a 2 μm thick SiO_2 film, and the etching solution was TMAH.

3.1
Thick structures with arbitrary shapes and thin suspended structures

This fabrication platform has successfully fabricated various thick structures such as mesa and post with arbitrary shapes. A typical example is the 80 μm thick circular mesa shown in Fig. 3a. As shown in Fig. 2d, e, the shape of the circular mesa was generated by DRIE, and all of its sidewall was covered with a 2 μm thick SiO_2 protecting structure. Hence, the non {111} crystal planes of the circular mesa was not attacked by TMAH during wet anisotropic etching in Fig. 2g. In addition, this platform can also fabricate various thin suspended structures. A typical example is the 2 μm thick SiO_2 cantilever shown in Fig. 3b. As shown in Fig. 2f, g, there was not any protecting structure on the convex corners and sidewall of the cantilever, so that it was released from the substrate using the undercut effect during wet anisotropic etching.

3.2
Stepped structures

The RIE lag and {111} crystal planes were employed to fabricate stepped structures for this platform. Two typical stepped structures fabricated using this platform were demonstrated in Fig. 4. The cross section view of these two stepped structures illustrated in Fig. 4a

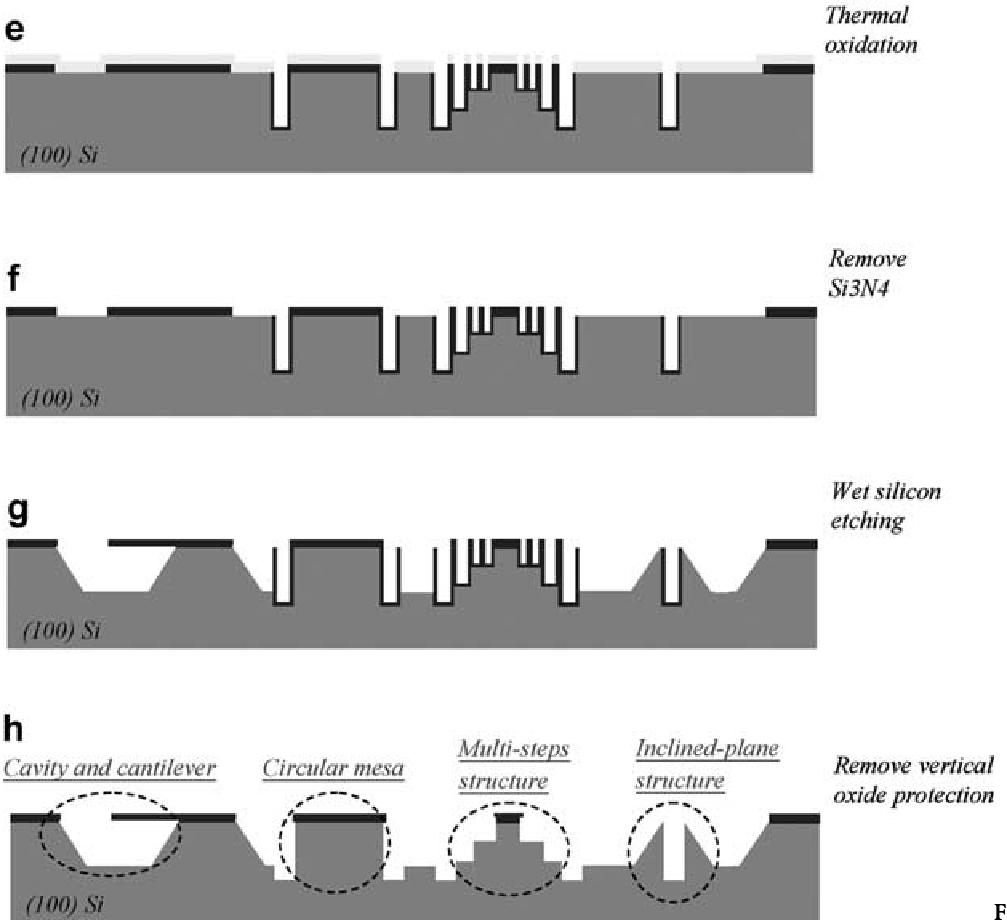

Fig. 2. (Continued)

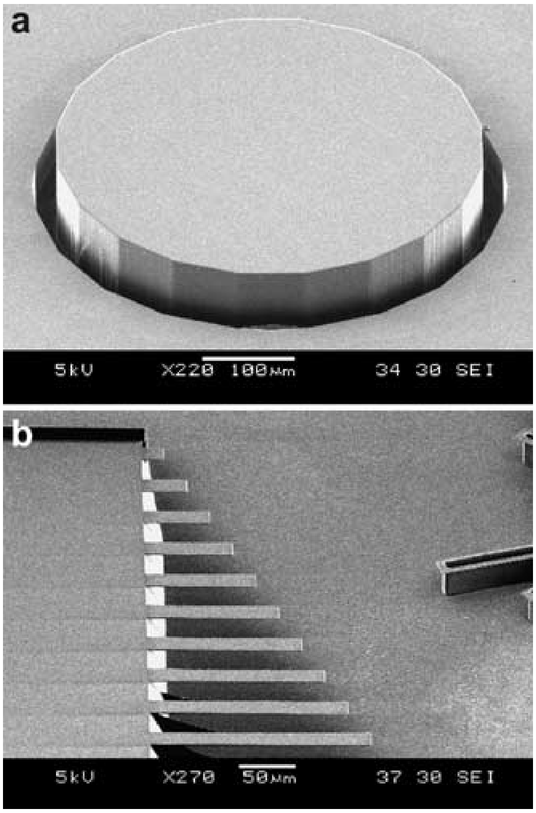

Fig. 3a,b. Some typical structures fabricated using the presented platform, **a** thick mesa, and **b** thin suspended beam

indicates that they had five different level depths. The top level (level 1) was the original surface of the substrate and did not experience any etching processes. Hence, the depth of level 1 was regarded as 0 µm. The second and third levels were only defined by the wet etching shown in Fig. 2g. Since the second level employed the {111} crystal planes to stop the anisotropic etching, its depth was different from that of the third level. The depth of level 2 and level 3 were 30 and 57 µm, respectively. As shown in Fig. 2c–h, the depths of forth and the fifth levels were mainly resulted form the DRIE etching. As indicated in Fig. 2c, the line patterns on the etching mask are all 2 µm wide, however, the spacing between these lines is different. Therefore, various etching depths were produced as shown in Fig. 2d after DRIE due to the RIE lag effect. The 2 µm thick silicon line structures were fully oxidized after the thermal oxidation shown in Fig. 2e. As shown in Fig. 2h, the oxidized line structures were etched away by BOE and formed the forth and the fifth levels of stepped structures in Fig. 4a. The depth of level 4 and level 5 were 91 and 108 µm, respectively. It is possible to further increase the step number of the structures after properly combining these two characteristics.

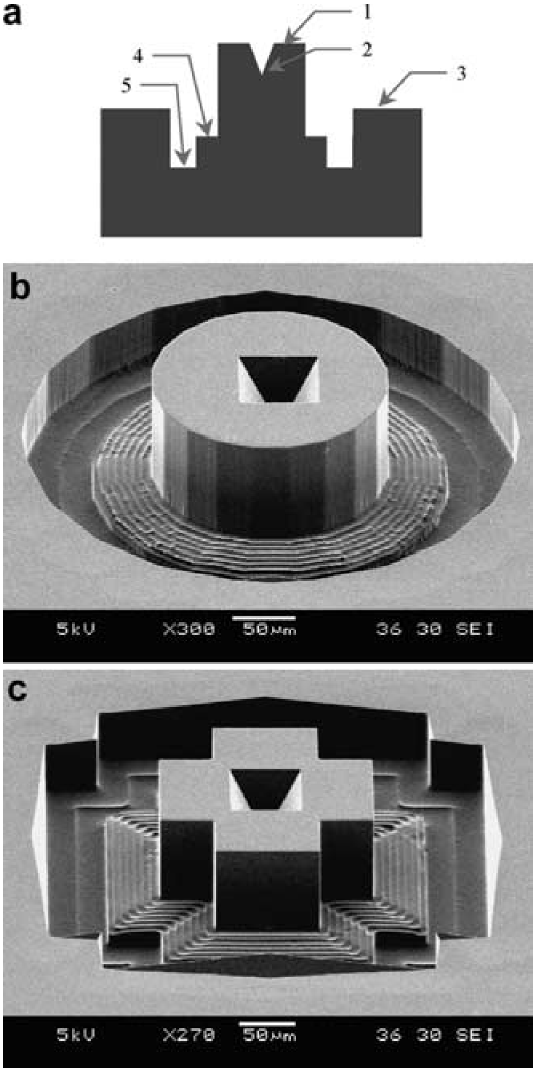

Fig. 4a–c. Two typical stepped structures fabricated using this platform, **a** the cross section view, **b** the circular stepped structure, and **c** the cross shape stepped structure

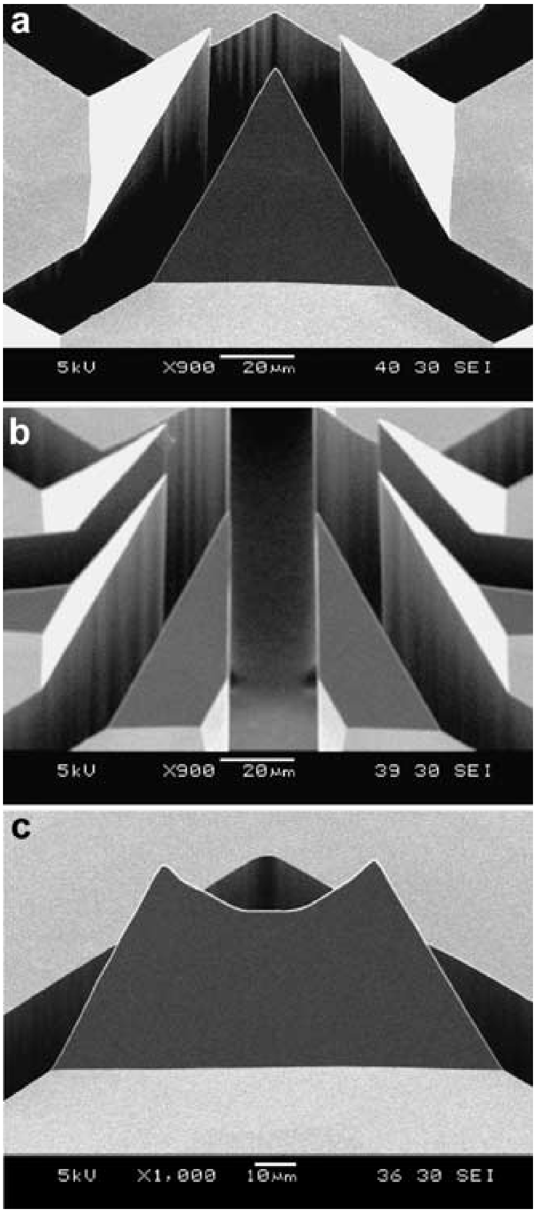

Fig. 5a–c. Typical pyramids fabricated using this platform, **a** the four pyramids, **b** the eight pyramids, and **c** the complicated pyramid

3.3
Structures with both inclined and vertical sidewalls

The DRIE generally produces vertical sidewalls for microstructures, whereas wet anisotropic etching generally produces inclined sidewalls formed by {111} crystal planes for microstructures. The presented platform has combined these two different etching mechanisms to fabricate microstructures with both inclined and vertical sidewalls. As shown in Fig. 2d–f, the silicon substrate was removed using DRIE to form vertical sidewalls first, and then grown a protecting structure on them. As shown in Fig. 2g, the wet anisotropic etching was employed to generate the inclined {111} sidewalls. The non {111} vertical sidewalls were covered with the protecting structures, and they were not attacked during wet anisotropic etching. The microstructures with both inclined and vertical sidewalls were available after the protecting structure was removed, as shown in Fig. 2h. The typical fabrication results shown in Fig. 5a are four pyramids, and each pyramid has two vertical sidewalls and one inclined {111} sidewall. Apparently, these pyramids were fabricated after the {111} planes divided by a cross shape protecting structure. Similarly, the eight pyramids in Fig. 5b were fabricated after the {111} planes divided by an asteroid shape protecting structure. The SEM photos show that the pyramid in Fig. 5b is sharper than that in

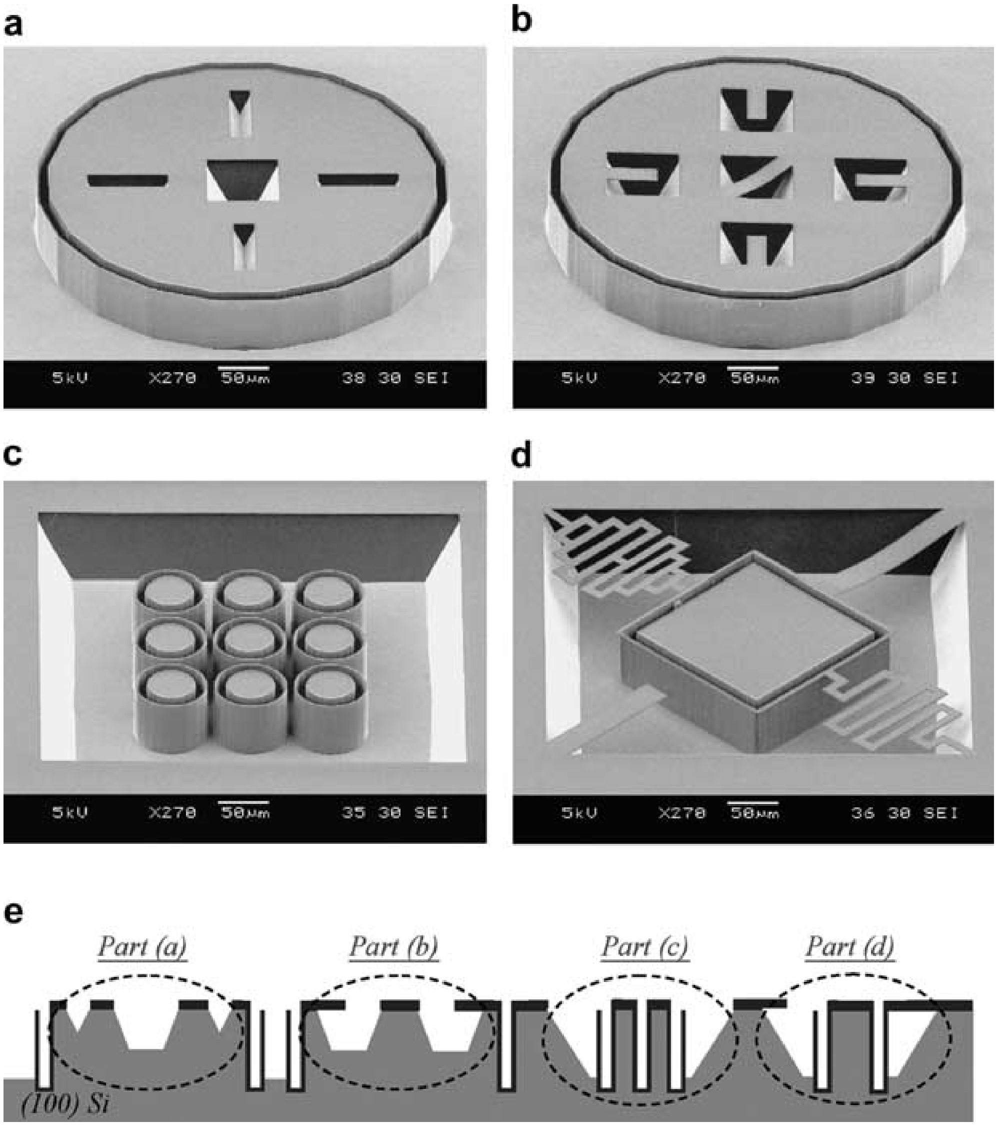

Fig. 6a–e. Integration of the suspended structure, V-groove, cavity, and mesa on the substrate, **a** the V-groove, cavity, and mesa, **b** the suspended structure, cavity, and mesa, **c** the cavity and mesa, **d** the suspended structure, cavity, and mesa, and **e** the side view of the aforementioned structures

Fig. 5a. Moreover, the complicated structure in Fig. 5c was fabricated after the {111} planes divided by a circular shape protecting structure. In summary, it is possible to construct various three-dimensional microstructures by combining the inclined {111} sidewalls with protecting structures.

3.4
Structure integration

The structures presented in Figs. 3, 4, 5 were all fabricated using the fabrication platform illustrated in Fig. 2. It is possible to integrate part or all of these structures for various applications. The following cases were employed to demonstrate the potential combination of these structures.

The suspended structure, V-groove, cavity, and mesa were integrated on the substrate based on the concept presented in Sects 3.1 and 3.3. As shown in Fig. 2d, e, the mesa with arbitrary shape was patterned by DRIE, and all of its sidewall was covered with a 2 µm thick SiO_2 protecting structure. Before wet anisotropic etching, various openings were defined on the etching mask either inside or outside the circular mesa. After that the wet anisotropic etching was employed to remove the silicon substrate and generate the inclined {111} sidewalls, as shown in Fig. 2g. As shown in Fig. 6a, b, the silicon substrate was removed by the wet

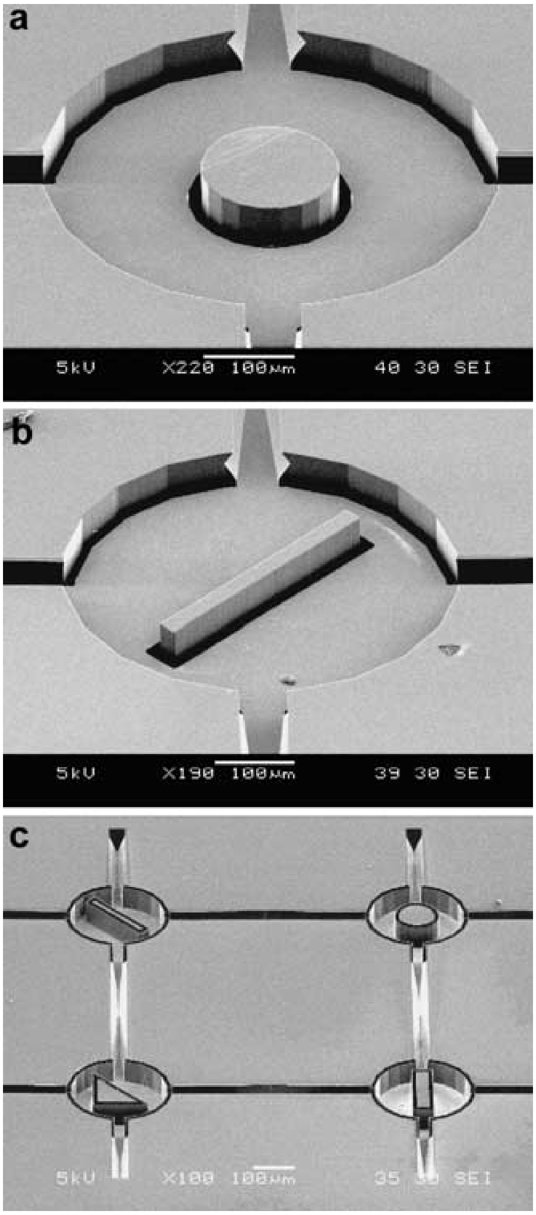

Fig. 7a,b. Integration of the V-groove, cavity, and mesa on the substrate, **a** the circular cavity and circular mesa, **b** the circular cavity and rectangular mesa, and **c** the V-groove, circular cavity, and mesa

anisotropic etching to form a circular mesa. In addition, the V-grooves, cavities, and suspended structures in the interior of the mesa were also fabricated using the wet anisotropic etching. In Fig. 6c, d, the silicon substrate was also removed by the wet anisotropic etching to produce nine circular posts and one square post, respectively. These posts were located inside a large cavity resulted from the wet anisotropic etching, and the {111} plane sidewalls can be clearly observed from the SEM photos. Moreover, the design in Fig. 6d further employed the undercut effect to fabricate the suspended structures. The schematic illustration in Fig. 6e shows the side view of the structures in Figs. 6a–d.

As a second example, the DRIE in Fig. 2d was used to define a circular cavity first. In the mean time, posts with arbitrary shapes were also defined by DRIE in the interior of the cavity. As shown in Fig. 2e, the sidewalls of the cavity and the post were covered with a 2 µm thick SiO_2 protecting structure. After wet anisotropic etching, the substrate inside the cavity yet outside the post was removed, so as to produce the structures shown in Fig. 7a, b. Moreover, the V-groove was also fabricated during wet etching, as shown in Fig. 7c. Thus, these V-grooves can perform as interconnections of the cavities. According to the processes mentioned in Sect. 3.3, the pyramid structure can be fabricated inside the cavity. A typical example is shown in Fig. 8. In this case, the cross shape protecting structure instead of the posts was placed inside the cavity to divide the {111} planes, as shown in Fig. 8a. Thus, four pyramids were fabricated inside the circular cavity after the protecting structure was etched away, as shown in Fig. 8b. The SEM photo in Fig. 8c is the close-up view of these four pyramids.

The last example shows the integration of the cavity and the stepped structure. As shown in Fig. 9, two different stepped posts are located inside the cavity. As mentioned in Sect. 3.2, the stepped structure due to RIE lag was patterned, etched, and oxidized firstly, as shown in Fig. 2c–f. In the mean time, the openings were also defined on the etching mask for the following wet anisotropic etching, as indicated in Fig. 9a. Hence, the silicon substrate under these openings was etched anisotropically, and the {111} planes formed the etching stop layer. The depth d indicated in Fig. 9a was mainly determined by the wet etching. Since a large opening was placed outside the stepped posts, they were surrounded by a cavity, as shown in Figs. 9b, c. The cavity inside the stepped post was also obtained in the same manner. Moreover, it is also obtained from Fig. 9b, c that the wet anisotropic etching was able to tune the depth of the cavity *d*. In other words, the wet anisotropic etching can be exploited to tune the depths of level 3 and level 5 for the stepped structure in Fig. 4a.

All of the aforementioned structures were fabricated using the platform processes illustrated in Fig. 2. In summary, the fabrication platform presented in this study enables the monolithic integration of these structures on a silicon substrate, as demonstrated by the SEM photos in Fig. 10.

4
Conclusions

This study presents a bulk micromachining fabrication platform on the (100) single crystal silicon substrate

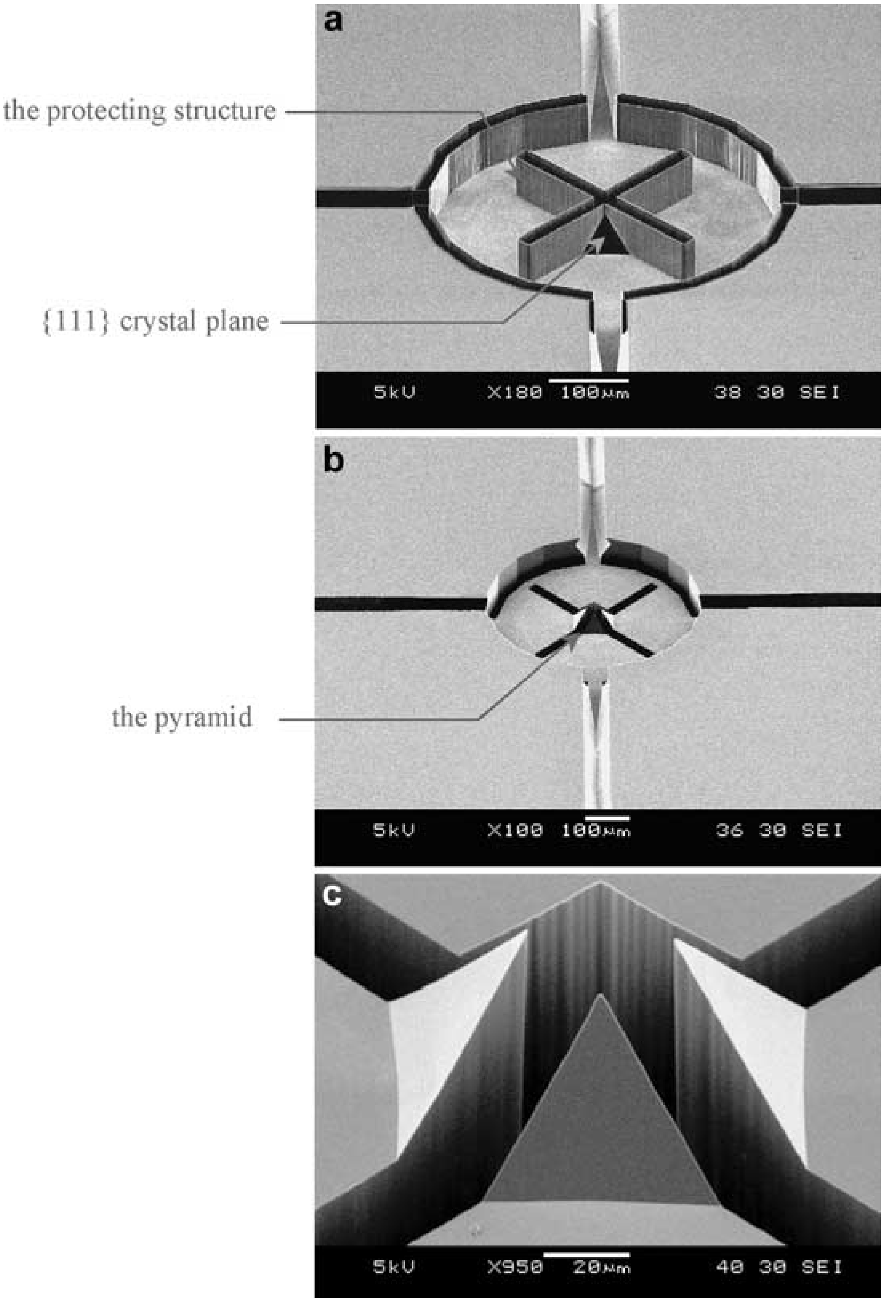

Fig. 8a–c. The pyramid structure fabricated inside the cavity, **a** the cross shape protecting structure, **b** four pyramids, and **c** the close-up of pyramids

using the integration of DRIE and the wet anisotropic etching. This platform employs the characteristics of the DRIE process to prevent the convex corner undercut and crystal plane dependent effect during bulk etching. The protecting structures are then grown or deposited to protect the convex corner and fast etching crystal planes. Thus, the mesas with even circular and triangular shapes become available after wet anisotropic etching. In addition, the RIE-lag in DRIE combines with the {111} crystal planes are used to fabricate the stepped-structures. The undercut will selectively occur at the convex corner without protecting structures, yet free suspend thin film structures remain available through the bulk silicon etching. Thus, the characteristics of wet anisotropic etching are exploited to provide V-grooves, pyramid cavities, and various suspended structures. Since all of the aforementioned structures can be fabricated and integrated using the presented fabrication platform, the applications of the bulk micromachining processes will significantly increase.

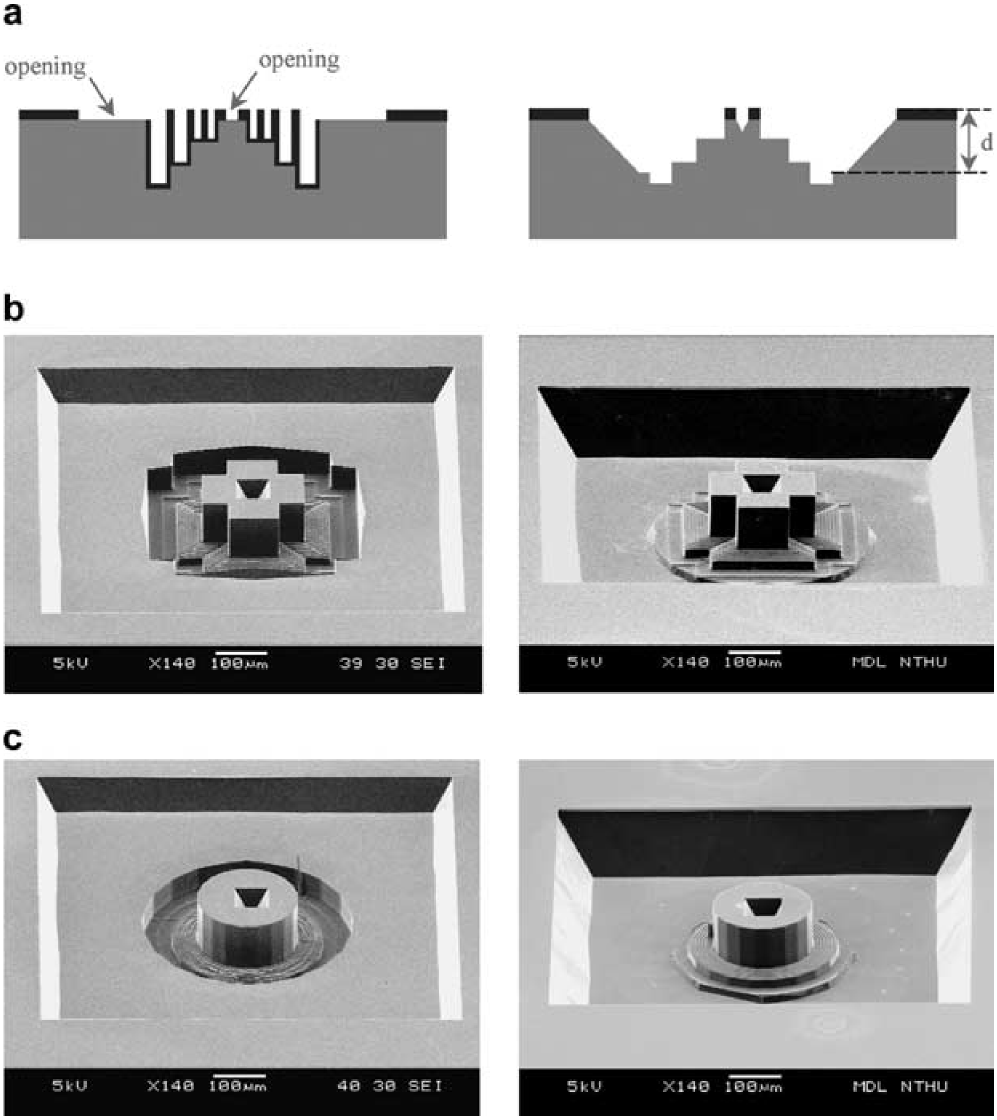

Fig. 9a,b. Integration of the cavity and the stepped structure **a** the schematic drawings of the cross section view, **b** cavity with d = 80 μm, and **c** cavity with d = 140 μm

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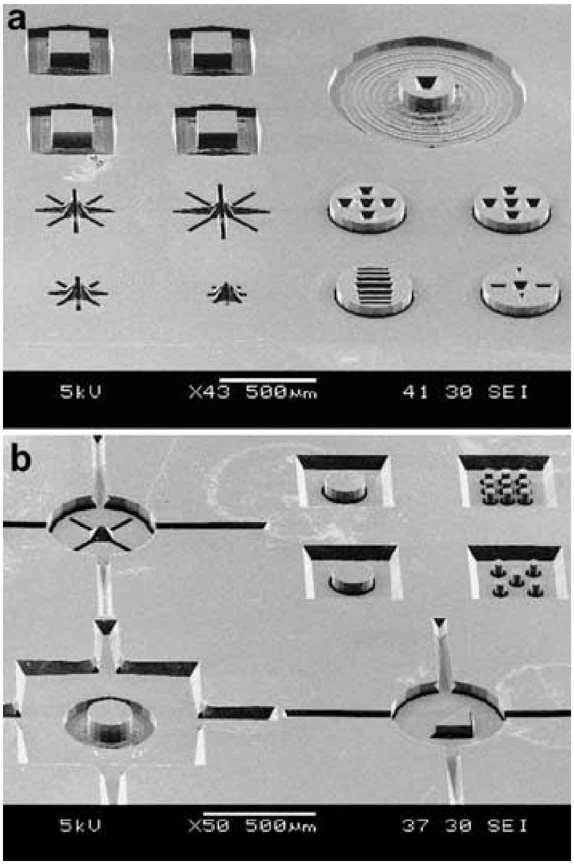

Fig. 10. Monolithic integration of the aforementioned structures on a silicon substrate

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