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# A COMPARISON OF DIFFERENT CONVEX CORNER COMPENSATION STRUCTURES APPLICABLE IN ANISOTROPIC WET CHEMICAL ETCHING OF {100} ORIENTED SILICON

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***Abstract:*** *This paper presents fabrication of microcantilevers on {100} oriented Si substrate by bulk micromachining. Two types of CCC (Convex Corner Compensation) structures, namely ⟨100⟩ oriented simple beam and structure using symmetric rectangular blocks oriented in the ⟨110⟩ direction at the apex of the square peg have been analyzed. Etching solution has been KOH water solution (80 wt. %) at etching temperature of 80 $^oC$. Detailed construction and etching behavior of both structures have been given and explained.*

***Keywords:*** *anisotropic wet chemical etching, bulk silicon micromachining, convex corner compensation, KOH etching solution, microcantilevers.*

## 1. INTRODUCTION

The fabrication of micro-electro-mechanical structures (MEMS) is generally referred to as micromachining [1,2]. Among different micromachining techniques [3] for manufacturing different micro and nano structures, wet anisotropic etching has prominent part till the very beginning of the development of MEMS technologies during sixties of the 20th century [4,5].

There is a high demand for 3D structures with a diversity of shapes including membranes, "bossed-type" features, suspended beams of different shapes, seismic masses, channels, etc. However, the ranges of the obtainable shapes are limited [6]. During the course of anisotropic etching, different crystallographic planes have different etching rates [7,8]. Because of the differences in the etching rates some planes grow, while others disappear. While etching a peg-like structure (the so-called mesa structure) with convex corners the fast etching planes dominate, i.e. fast-etching planes increase in length while slow etching planes decrease and finally disappear, changing the overall island shape. This is an inherent feature of anisotropic wet chemical etching and, as a consequence, severe convex corner undercutting distorts the desired shape of the structure. Therefore, in such cases, it is highly desirable to eliminate the undercutting by some means, e.g. by the design and application of some convex corner compensation (CCC) structures.

Shape and dimensions of this additional structures constructed at the corners which have to be preserved during etching, depend on the type of etching soution and on spatial requirements. It turns out that all this claims become more severe as the mesa structure become higher. Generally speaking, every particular shape with defined heght have optimum CCC structure with dimensions obtained from experimental considerations for specific etching solution.

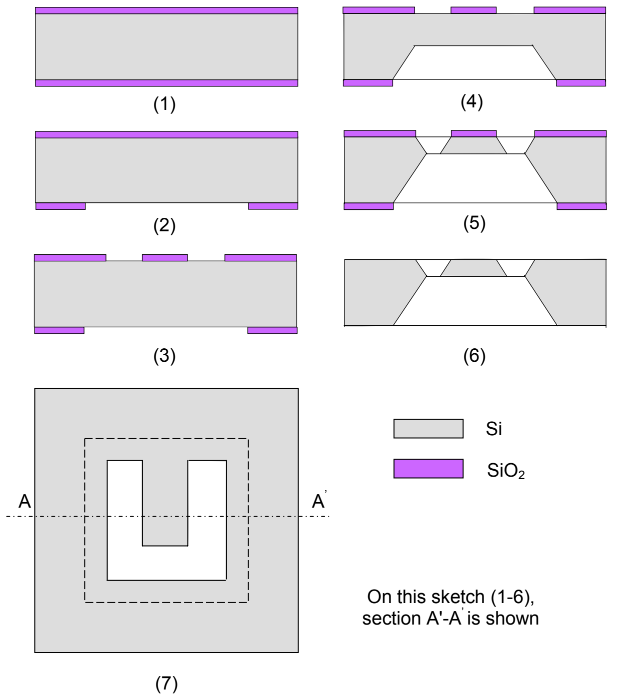
In this paper we are going to work out two types of CCC structurs, namely: ⟨100⟩ oriented bar [9] and structure which contains two rectangular blocks placed perpendicular with respect to each other at the appex of convex corner which have to be protected [10]. This structures are both applicable for fabrication of silicon microcantilever using bulk micromachining on {100} oriented silicon substrate. Solution for wet anisotropic etching have been 30 wt% KOH water solution at 80 °C.

## 2. EXPERIMENTAL

N-type {100} oriented Si wafers, 400 ± 25 μm thick, both sides mirror polished, with the resistivity 5-3 Ω·cm have been used for microcantilever fabrication.

The silicon dioxide was used as a masking material in all etching steps of microcantilever fabrication. $SiO_2$ (at least 1.4 μm thick) has been thermally grown in atmosphere of water saturated oxygen at 1050 °C, and patterned in classic photolithography process using EVG®620 tool designed for optical double-side lithography from "EVG group company".

Bulk micromachined microcantilevers are oriented in ⟨110⟩ direction, and sketch of successive fabrication steps is given in Picture 1. All orientation alignments have been done toward primary flat direction: ⟨110⟩ ± 0.5 °.




**Picture 1.** Sketch of fabrication steps of ⟨110⟩ oriented Si microcantilever on {100} Si wafer. Anisotropic wet etching is performed from both sides of the wafer, thanks to double side alignment during photolithography.

The etching process was carried out in thermostated Pyrex vessel containing about 0.8 $dm^3$ solution allowing the temperature stabilization within ± 0.5 °C. The vessel is sealed with a screw on lid which included a tape water cooled condenser, to minimize evaporation during etching. During etching, the solution is electromagnetically stirred with 300 rpm and the Si wafers were held vertically inside the etching solution.

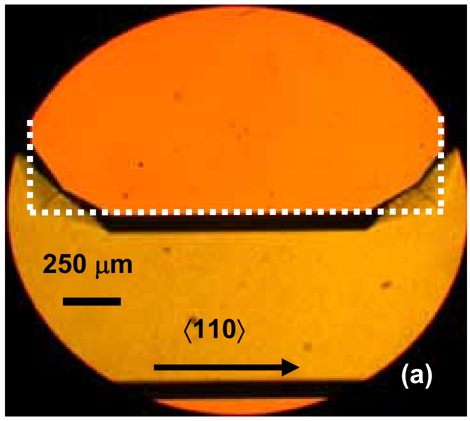
As an example we are going to present fabrication of microcantilever of 100 μm thickness. As can be seen from Fig. 1, first silicon etching step (4) was done from the back side. During this step half of the wafer thickness (~ 200 μm) has been etched away from the back. Front side was protected during this etching step. During next step (5) wafer is etched from both sides, and in this step microcantilever beams are formed when substrate becomes etched through on unmasked parts. In this step compensation structure play remarkable role of protecting convex corner at the beam end from undesired undercutting.

Connection between etching depth ($d$) and etching time ($\tau$) is given as:

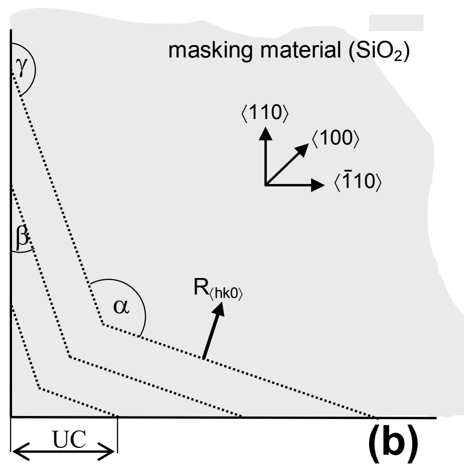
$$\tau = R_{\langle 100\rangle} \cdot d \qquad (1)$$

where $R_{\langle 100\rangle}$ is the {100} oriented Si substrate etching rate.

To determine what crystallogrphic plane is the fastest etching plane in considered solution, we did etching under the same conditions on structure schematically depicted in Picture 2. This structure has same orientation as microcantilever, e.g. edges of convex corners are oriented in ⟨110⟩ direction.




**Picture 2. (a)** Photograph from the metallurgical microscope of convex corners on the square island with edges oriented along ⟨110⟩ directions on {100}oriented Si wafer after etching in 30 wt% KOH solution at 80 °C during 120 min. White interrupted line shows border of square island as was defined during photolithograhy on masking material.




**Picture 2. (b)** Schematic of convex corner structure used to determine undercutting (UC) and angle β.

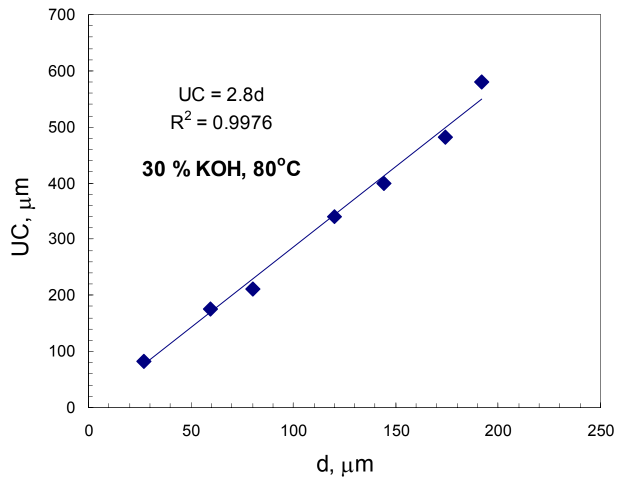
Dependence of undercutting, denoted as UC in Picture 2, on etching depth ($d$), or time of etching ($\tau$), is indispensable requirement for the analysis of design of CCC geometries [11-13].

For the structure shown in Fig. 3, it can be shown that undercutting is given as:

$$UC = \frac{K}{\sin\beta} d \qquad (2)$$

where $K$ is the ratio of etch rates ($R_{\langle hk0\rangle} \cdot R_{\langle 100\rangle}^{-1}$), $d$ is etch depth and β is angle between ⟨110⟩ and ⟨hk0⟩ directions.

Diagram in Picture 3. is experimentally determined dependence of convex corner undercutting, $UC$, on etched depth, $d$, for 30 wt. % KOH water solution at 80 °C.




**Picture 3.** Dependence of corner undercutting ($UC$) on etching depth ($d$) for anisotropic wet etching in 30 wt. % KOH water solution. Edges of square island are oriented parallel with ⟨110⟩ direction on {100} oriented Si substrate.

From the slope of straight line and knowledge of the measured value of angle $\beta$, it is possible to determine value of constant K according to eq. (2) for applied solution.

Obtained results are summarized in Table 1. In this table nature of the fast etching planes are designated for 30 wt % KOH solution at 80°C.

Other characteristics of investigated solutions which are important for microcantilever fabrication by bulk micromachining of Si are also given in above mentioned table.

**Table 1.** Important etching properties of 30 wt. % KOH solution at 80°C

| $R_{\langle 100\rangle}$, μm·min$^{-1}$ | K | $R_{\langle hk0\rangle}$, μm·min$^{-1}$ | UC·d$^{-1}$ | α, ° | β, ° | γ, ° |
|---|---|---|---|---|---|---|
| experimental results | | | | | | |
| 1.2 | 1.4 | 1.7 | 2.8 | 149.2 | 29.7 | 150.4° |
| calculated angles for ⟨410⟩ | | | | | | |
| | | | | 151.9 | 30.9 | 149.0 |

## 2. RESULTS AND DISCUSSIONS

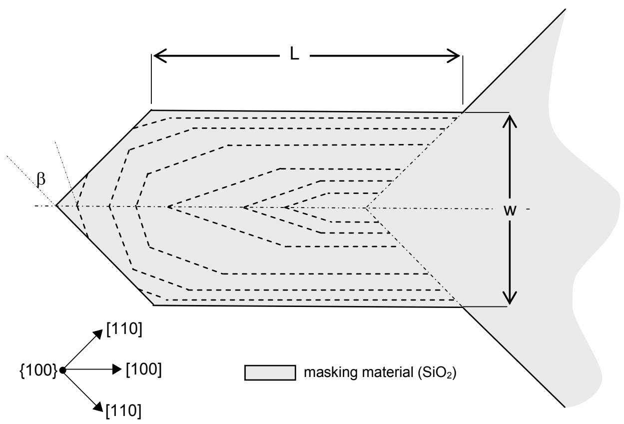
Picture 4. shows sketch of etching front progress during the course of ⟨100⟩ compensation beam etching.

From the geometry considerations from Picture 4, it can be shown that [14]:

$$L = d\left(\frac{\sqrt{2}}{\cos\beta - \sin\beta} \cdot \frac{R_{\langle hk0\rangle}}{R_{\langle 100\rangle}} - \frac{2\sin\beta}{\cos\beta - \sin\beta}\right), \qquad (3)$$

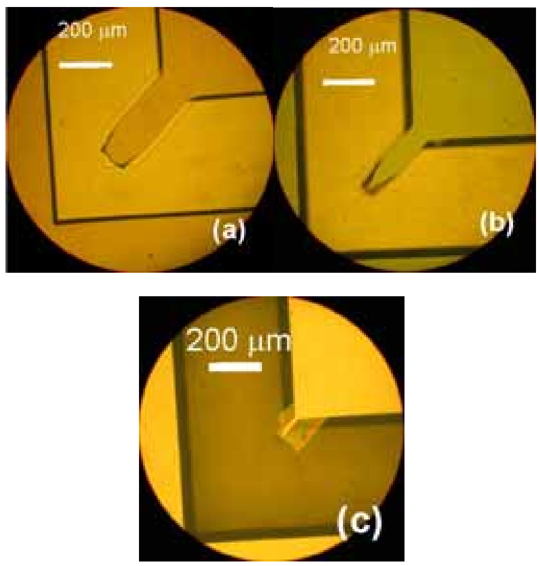
$$w = 2d, \qquad (4)$$

where $L$ and $W$ are CCC length and width, respectively, β is angle between ⟨110⟩ and ⟨hk0⟩ directions, and $R_{\langle hk0\rangle}$ is the etching rate of the fastest etching plane {hk0} at the convex corner.




**Picture 4.** Schematic representation of successive etch fronts for used corner compensation structure, namely ⟨100⟩ oriented beam.

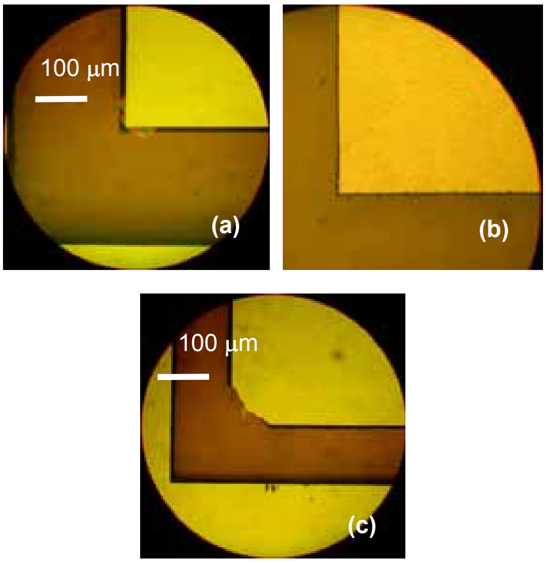
From Table 1. it can be seen, that the fastest etching plane belongs to the ⟨410⟩ family and with given parameters dimensions of CCC ⟨100⟩ oriented beam structure can be obtained for desired etching depth (d).



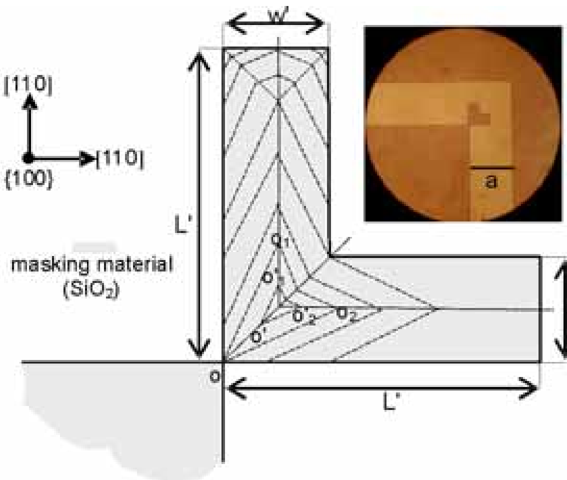

**Picture 5.** Photographs from the metallographic microscope of successive etching steps of ⟨100⟩ compensation beam on the corner of the microcantilever

oriented on ⟨110⟩ direction on Si {100} oriented wafer. Etching solution is 30 wt. % KOH solutions at 80°C. Etching times are 20 min (a), 45 min (b) and 90 min (c).

Picture 5. displays photographs from metallographic microscope of successive etching steps of ⟨100⟩ oriented compensation beam etched in KOH solution. Picture 5, (a) and (b) are photographs of preserved convex corner at microcantilever edge obtained applying ⟨100⟩ oriented compensation beams.




**Picture 6.** Photographs from the metallographic microscope of fabricated microcantilever's convex corner. Applied compensation is ⟨100⟩ oriented beam, and etching was performed in 30 wt. % KOH solution at 80°C. (a) Is corner appearance from the front side with masking material, (b) is the same corner as in (a) from the back side, (c) is the convex corner without any compesation etched under same condition.

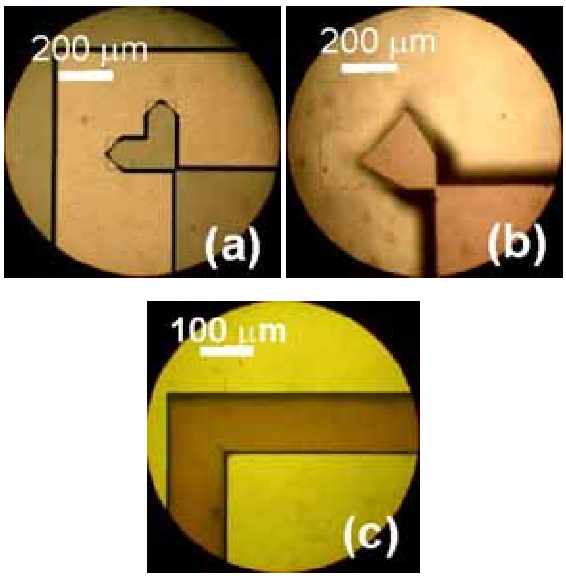



**Picture 7.** Schematic representation of successive etching steps for CC structure with symmetric rectangular blocks at the island's apex with edges oriented along ⟨110⟩ directions on {100} oriented Si wafer.

Sharp right angled corner with no deformation may be obtained by applying ⟨100⟩ oriented compensation beam with dimensions calculated in accordance with eq. (4), for beam width, and eq. (3) for beam length. Picture 6. shows how well is CC preserved applying such compensation looking from the front (a), and from the back (b) of fabricated microcantilever. Photograph in Picture 6. (c) is given for comparison to notice convex corner shape after anisotropic wet etching without applying additional structure for convex corner compensation.

Schematic representation in Picture 7. presents shows etching steps of second applied CCC structure in the form of symmetric rectangular blocks at the very apex of convex corner.

At the right corner of this figure photograph from metallurgical microscop of one CCC on microcantilever immediately before anisotropic etching is given. With "a" is denoted length of free space which is on disposal for constructing CCC structure. Looking in on this schematic representation we must have in mind that this is etching from both sides. When the etching front $OO_1O_2$ is reached, the convex corner is defined since substrate must be etched through in that moment of etching. If this is not truth, i.e. the etching proceeded from both sides, we are going to reach figure $O'O'_1O'_2$ and convex corner at O should be undercutted.




**Picture 8.** Photographs from the metallographic microscope of successive etching steps for CC structure with symmetric rectangular blocks at the island's apex with edges oriented along ⟨110⟩ directions on {100} oriented Si substrate. Etching solution is 30 wt. % KOH at 80°C. Etching times are 20 min (a), 51 min (b) and 65 min (c).

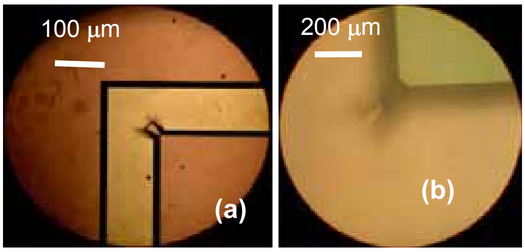
In Picture 8. successive etching steps of this type of compensation are given. On picture 8. (c) is shown the last step after which front and back side etching must meet if we want to preserve convex corner at the microcantilever.

Applying the same strategy as for previous compensation and having in mind that the etching figure $OO_1O_2$ have to be reached, we can calculate length of compensation (*L*') and its width (*w*') as:

$$L' = d\frac{K}{\sin\alpha}, \quad (5)$$

$$w' = \frac{L'(1-\sin\alpha)}{\cos\alpha}, \quad (6)$$

where all symbols have already been explained.




**Picture 9.** Second compensation on convex corner, but anisotropic wet etching is done from the front only.

In Picture 9. are two examples of anisotropic etching which is applied only from the front side of wafer. It can be seen that in (a) is a moment when substrate must be etched completely to preserve convex corner. In (b) it is clearly seen that further etching results in corner undercutting.

From these experimental results we can say that both applied compensation for convex corners can be successfully applied during silicon microcantilevers fabrication by bulk silicon micromachining.

Also we can say that second compensation is more space consuming. For CCC structure with symmetric rectangular blocks at the island's apex with edges oriented along ⟨110⟩ directions, the length of the free space ("a" in Picture 7) must be wider than the length of compensation (L'). In the case of fabrication microcantilever with 100 µm thickness, length of compensation structure is 272 µm, which require free space of at least 300 µm.

When the compensation structure is ⟨100⟩ oriented beam, required free space must be wider than L·cos45$^o$, which is less than in the previous case.

## 5. CONCLUSION

A detailed investigation have been carried out to study prevention of convex corners undrcutting during fabrivation of silicon microcantilever beam released by bulk silicon micromachining applying anisotropic wet etching in 30 wt. % KOH solutions at 80 $^o$C. Microcantilevers were fabricated on {100} oriented silicon substrate by anistropic etching from both sides.

Two types of CC compensation structures have been applied: simple ⟨100⟩ oriented beem and symmetric rectangular blocks at the island's apex with edges oriented along ⟨110⟩ directions.

Determination procedures for the fastest etching plane and ratio of etching rates of this plane and the substrate plane were described. These data, together with microcantilever dimensions, are necessary for determination of compensating structures dimensions.

Based on experimental results for etching rate of the fast etching plane and ratio of etching rates for this plane and the substrate plane, lengths and widths for a given microcantilever thickness were derived.

It was found that both compensation structures perform well, i.e. thay can preserve shape of convex corner. But it is obvious that symmetric rectangular blocks at the island's apex with edges oriented along ⟨110⟩ directions compensation can be applied only when the anisotropic etching is performed from both wafer's sides simultaneously. Also, this compensation structure is more space consuming.

## ACKNOWLEDGEMENT

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