# The Optimum Condition of Anisotropic Bulk (110) Si Etching with KOH for High Selectivity and Low Surface Roughness

Hyung-Teak Lim, Yong-Kweon Kim, and Seung-Ki Lee

## Abstract

In this paper, the optimum condition of (110) Si etching with the potassium hydroxide(KOH) etchant is presented. Although several researches on (110) Si anisotropic etching have been studied, there has been lack of effects of mask quality and etching conditions on the selectivity and the roughness on the etched surface. Three kinds of masks(film, emulsion and E-beam mask) were used in order to verify the effect of etching properties. Anisotropic bulk etching depends on the crystalline orientation and the concentration and temperature of the etchant. In order to investigate the effect of etching conditions on selectivity and the roughness of the etched surface, the concentration of the etchant was varied from 35 to 45 per cent in weight with increments by 5 per cent and the temperature was changed from 70 to 90℃ with increments by 10℃. The combination of the temperature of 70℃ and the concentration of 40 wt.% was found to be the optimum etching condition for high selectivity. Etched surfaces show minimum surface roughness at a temperature of 80℃ and a concentration of 40 wt.%. Comb structures with various comb widths were fabricated and the lengths of the combs were measured with several etching time durations. A micro comb structure 525μm high was fabricated for MEMS application.

## I. Introduction

Micro electromechanical systems (MEMS) devices have been developed by the introduction of three-dimensional microstructure using CMOS-compatible fabrication processes. The processes offer low cost and mass production by highly controllable and reproducible fabrication technology. Great efforts have been made in the application of these structures to the micro sensors and actuators that have been given conspicuous notice in commercial and military systems. Typical examples of applications are accelerometers, gyroscopes, surface acoustic wave (SAW) devices, micro mirrors, micro pumps and ink jet nozzles[1-5]. However, there are some limitations and problems remaining in the manufacture of these devices using current fabrication technology. These are:

1) How to fabricate structures with high-aspect ratios.
2) How to fabricate a structure with large thickness.
3) How to excite a mechanical motion in micro actuators.
4) Generally, the best physical and mechanical properties of deposited layers do not coincide with the best electrical properties.

In the case of the fabrication of micro structures using surface micromachining, new problems of mechanical properties and internal residual stress occur that would not occur at macro model sizes [6]. Bulk micromachining, especially using (110) silicon, could solve these problems. With a (110) oriented wafer, it is possible to fabricate high-aspect ratio and thick structures by anisotropic bulk etching, which uses the difference of etch rate depending on the crystalline orientation[7]. Additionally, Silicon has no physical hysteresis, no internal stress and high conductivity.

There is an electrostatic method to induce a mechanical motion to MEMS[8, 9]. It has no mutual interference, no electrical hysteresis and a possibility to control a motion by simply applying an electric field.

The force that an electrically stimulated comb-drive actuator generates is inversely proportional to the gap distance and proportional to the height of the comb electrodes[10]. The electrodes must have a high-aspect ratio in order to generate a large force with a small voltage difference. Anisotropic etching of (110) Si is very useful for obtaining a high-aspect ratio structure[11].

In the (110) Si wafer, there are four (111) planes perpendicular to the wafer surface and two slant (111) planes which makes an angle of 35.26 with wafer surface. Considering these crystalline structures, it is required to estimate the reduction of comb length and compensate the design of comb structure.

For fabrication using orientation-dependent etching, it is very important to consider and scrutinize the effects of mask quality and the relationships between combinations of temperature and

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**Table 1.** Comparison of previous research with this work. - : No data

| Reference | | [12] | [13] | [14] | [15] | This work |
|---|---|---|---|---|---|---|
| use of alignment target | | - | Yes | Yes | - | Yes |
| experiment condition | roughness | fixed to 90℃ varying 10-60wt.% | fixed to 70℃ or 40wt.% | - | - | varying 70-90℃ and 35-45wt.% |
| | etch rate | fixed to 90℃. varying 10-60wt.% | - | fixed to 50℃ and 50wt.% | - | varying 70-90℃ and 35-45wt.% |
| | selectivity | fixed to 90℃ and 50wt.% | fixed to 70℃, varying 10-45wt.% | - | - | varying 70-90℃ and 35-45wt.% |
| fabricated structure | | groove(200$\mu$m) | groove | hole | comb(58$\mu$m) | comb(525$\mu$m) |

concentration of the etchant. Generally, there are three kinds of masks: film, emulsion, E-beam mask. Because (110) anisotropic etching is very sensitive to the sharpness of (111) oriented line of etch mask and the cost effectiveness of mask is not known, it is required to investigate the mask quality and etch profile. In previous researches, there has been a lack of consideration of relationship between the etching condition and the etched profile, as shown in Table 1.

In this paper, the effects of etching conditions on the selectivity and the roughness of the etched surface were investigated, varying the temperature of etchant from 70℃ to 90℃, and the concentration from 35 wt.% to 45 wt.%. In the actual wet etching process on (110) Si, the overlapping length of comb electrodes is reduced because the comb length reduces as the etching process progresses. The decrement lengths depending on the beam width were measured. An alignment target with 0.05 accuracy was used to verify a (111) orientation on (110) wafer. The cost effectiveness of mask quality was investigated.

## II. Alignment Target and Etching Bath

In all wafers, whether they are (100) or (110), there is the flat zone, or so-called primary flat, which indicates the (111) direction. However, this is only fabricated in mechanical machining and it has errors up to about ±1 relative to the precise (111) orientation. We must align the alignment target with the ready-made (111) direction (primary flat zone) on the wafer and etch the alignment target in order to verify the precise (111) direction. After etching the alignment target, the (111) direction can be proved by selecting the least undercut narrow beam. Figure 1 shows the etched alignment target for the purpose of finding the (111) orientation. Each beam has already been etched more than 100$\mu$m.

Each narrow beam was designed to make an angle of 0.1 degree. There are 100 beams and this target mask can cover an angle variation of crystalline orientation within a range of ±5 degrees from the primary flat. The more the narrow beam is misaligned to the (111) orientation of the silicon crystalline structure, the more the beam is substantially dissolved by anisotropic etching[16].

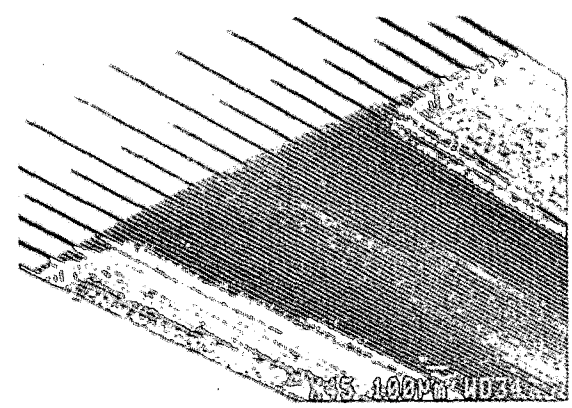


Fig. 1. SEM view of etched alignment target.

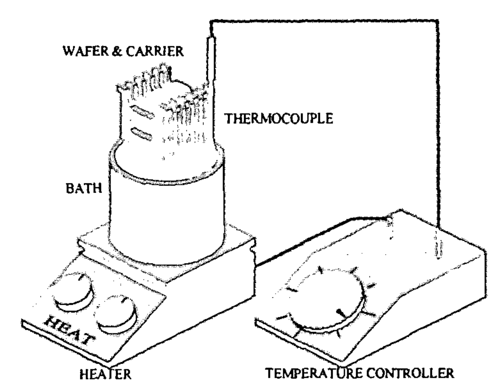



Fig. 2. Bath system composed of heater and controller.

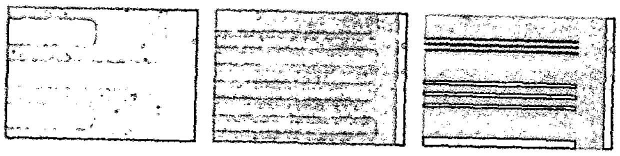
The etch-rate is much more sensitive to temperature than concentration. Thus, in the case of timed etching, it is necessary to control the temperature of the KOH etchant carefully. We made up of etching bath system composed of thermocouple, heater and temperature controller as shown in Figure 2.

## III. Fabrication of Comb Structures

In the design of comb structure to fabricate using the anisotropic etching, two factors that affect the fabrication of structure should

**Table 2.** Comparison of qualities among different masks.

| | Film mask | Emulsion mask | E-beam mask |
|---|---|---|---|
| resolution | 50$\mu$m | 10$\mu$m | 1$\mu$m |
| tolerance | 7-8$\mu$m | 2-3$\mu$m | 0.2$\mu$m |
| hardness | flexible | hard | hard |
| contrast | bad | good | excellent |
| cleanability | no | no | yes |
| number of times to use | several | less than 20 times | unlimited if cleaned |
| cost | $25 | $125 | $1400 |



(a) Film mask (b) Emulsion mask (c) E-beam mask

**Fig. 3.** Microscopic view of masks.

be considered. One is the inherent mask quality and the other is the reduction of beam length.

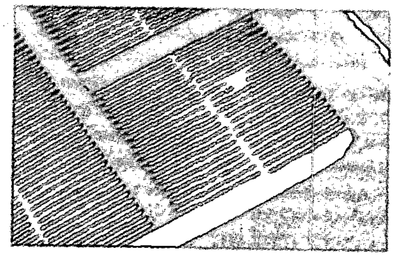
*1. Etching Profile Dependent on Mask Quality*

There are three kinds of masks (film, emulsion and E-beam masks) that we can generally choose as a photolithography mask for the micromachining process, as shown in Table 2.

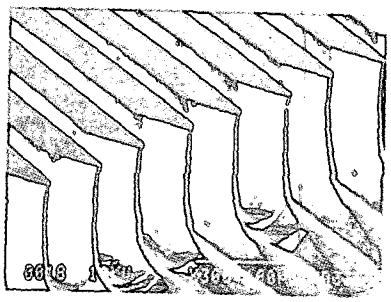
The masks differ in cost and quality. The intrinsic meaning of mask quality includes: the resolution to which the mask can realize a line width; how long the mask is durable; how many times we can use the mask reliably.

The comb structures were fabricated on a (110) Si wafer using a film mask. Because the resolution of a film mask is 50$\mu$m, we designed the width and spacing of the comb as 100$\mu$m and 50$\mu$m, respectively, as shown in Figure 3(a).

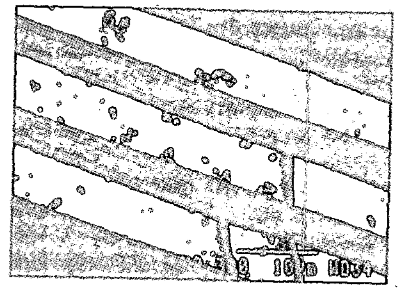
Because the deviation of straight lines in the mask is up to ten micrometers and the boundaries between the masking area and the non-masking area are not distinctive, these affect the photolithography process and result in the undercutting of patterns in the anisotropic etching process. The geometry of the fabricated comb structure is 75$\mu$m width, 75$\mu$m gap and 525$\mu$m height (the thickness of the wafer), as shown in Figure 4(a). It took approximately five hours to penetrate the wafer under the 40wt.% and 80℃ KOH solution. This etch rate is approximately 1.78$\mu$m/min. and the selectivity is approximately 45, which is a lower value than that obtained with emulsion and E-beam masks, as will be described below. Because the film mask is very flexible and sensitive to heat, its expansion affects mask distortion. A film has many defects and has a poor transparent rate. It often causes photolithography problems (the reduction of intensity of exposed light radiation).



(a) 525$\mu$m height structure fabricated with a film mask.



(b) 150$\mu$m height structure fabricated with an emulsion mask.



(c) 150$\mu$m height structure fabricated with an E-beam mask.

**Fig. 4.** Fabricated structures.

Boundaries are more distinctive for an emulsion mask than for a film mask and the minimum resolution of line width is about 10$\mu$m, as shown in Figure 3(b). We designed the width and spacing of the comb as 40$\mu$m and 20$\mu$m, respectively and performed the etching process for 100 minutes using 45wt. % and 80℃ KOH. The geometry of the fabricated comb structure is 35$\mu$m width, 25$\mu$m gap and 150$\mu$m height. Selectivity is about 55, as shown in Figure 4(b). An emulsion mask has limitations in cleaning and the number of times to be used, because its material is soft compared with an E-beam mask.

The resolution of an E-beam mask is about 1$\mu$m and the deviation is about 0.2$\mu$m. The masking material is metal and the boundaries are the most distinct, as shown in Figure 3(c). We designed a comb structure whose geometry was 10$\mu$m width, 10$\mu$m gap and 1㎜ length and fabricated the comb using a 40wt.% and 70℃ KOH solution for 100 minutes. The etched structure is shown in Figure 4(c). The geometry of the comb structure is 7$\mu$m width, 13$\mu$m gap and 150$\mu$m height. Selectivity is more than 90.

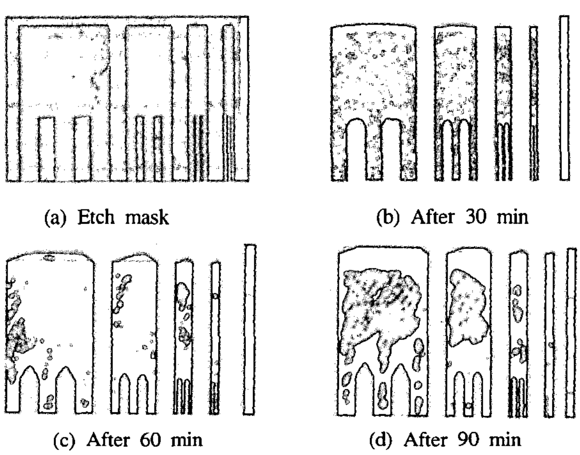
Although the etching temperatures and concentrations are not exactly the same, the fabricated structure using E-beam mask had the highest selectivity. It was caused by the sharpness of

(111) oriented line of the mask. However, although the E-beam mask was used, the fabricated structure didn't have such a high selectivity if the alignment was deviated from exact (111) orientation.

### 2. *Reduction of Beam Length*

For the fabrication of comb structures including any other structure on a (110) oriented wafer, it is very important to consider not only selectivity but also etching characteristics for directions and planes other than the <111> direction and (111) plane[17, 18]. Figure 5 shows the residual beam profile as the wet etching is processed for different beam width: 100, 50 and 20$\mu$m.

From these results, the beam length decreases with etching time and the decrement rate is strongly dependent on the beam width. At the initial stage of the etching process, as shown Figure 5 (b), the beams are hardly reduced by etching but form a wedge shape due to anisotropic etching. Thereafter, each beam length is reduced, sustaining the wedge shape formed by other planes. With longer etching times, the beam width becomes thinner by etching to (111) plane and the beam length is reduced. Throughout the etching process, narrow beams have their lengths reduced more quickly. We measured these residual beam lengths and plotted them in Figure 6.



(a) Etch mask (b) After 30 min (c) After 60 min (d) After 90 min

**Fig. 5.** Residual beam of different width of 100, 50, 20 and 10$\mu$m from left to right.

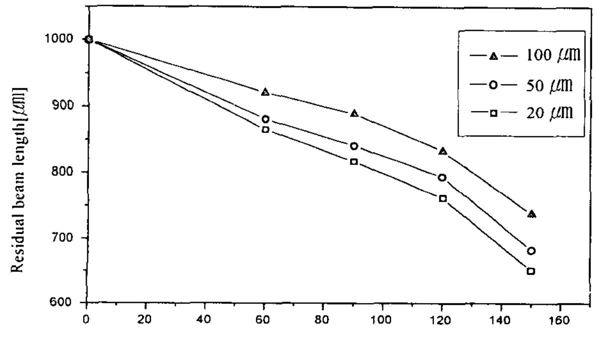
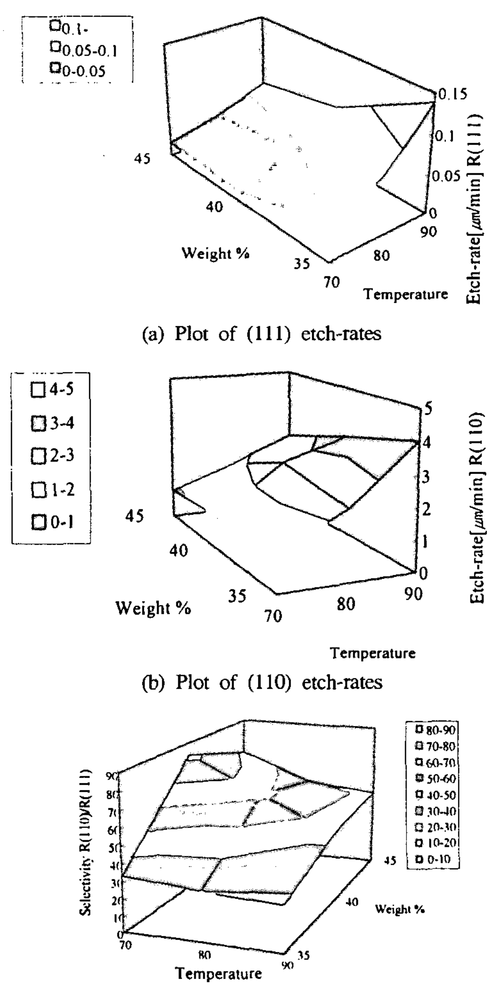



**Fig. 6.** Plot of residual beam length of different width with etching.

It is very important to consider beam length reduction in the design of comb electrodes, in order to fabricate the overlapped area between two different comb pairs. We must compensate with additional beam length for the desired beam structure of the mask, considering beam width and etching depth using this estimation.

## IV. Dependency of Profile on Concentration and Temperature

A test pattern using an E-beam mask was designed for a comb whose geometry is the same gap and width from 10$\mu$m to 100$\mu$m, respectively. The concentration of the etchant was varied from 35% to 45% in weight percent by 5% increments. The temperature was changed from 70℃ to 90℃ by 10℃ increments. At each condition, we measured the etched depth and the lateral width of the comb and calculated the selectivity between R(110)




(a) Plot of (111) etch-rates

(b) Plot of (110) etch-rates

(c) Plot of selectivities-R(110)/R(111)

**Fig. 7.** Plots of etch rates and selectivity with wt.% and temperature.

and R(111). Figure 7 shows the plots of etch rates in the <110> direction and <111> direction and a plot of selectivity value and shows the results and trends.

For either (110) or (111) etch direction, the etch rate increases with a higher temperature and a lower concentration of a Potassium Hydroxide (KOH) solution. The highest selectivity, more than 90, is obtained with a concentration of 40 wt. % and a temperature of 70℃. At lower temperatures, below 70℃, there would have been better selectivity.

However, at any other combination of the etchant, a roughness and a size of hillocks were outstanding. At the fabrication of comb structure whose geometry is less than 10$\mu m$ gap, the narrow etched region is obstructed by other planes like (311) plane, as shown in Figure 8. These made a bad effect on the selectivity and etch rate depending on its geometry.

The roughness of the etched bottom surface and the number of hillocks increased and the uniformity decreased with lower temperatures. At higher temperatures, the sizes of the hillocks also increased and the roughness increased abruptly. Figure 9 is a SEM photograph of the etched surface under different conditions

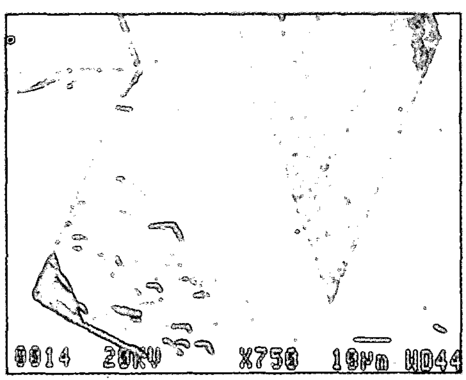
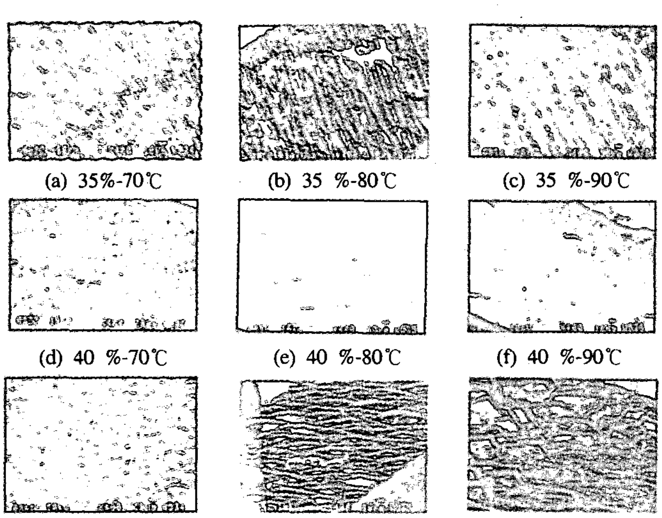


**Fig. 8.** Other plane in the etched region.



(a) 35%-70℃ (b) 35 %-80℃ (c) 35 %-90℃

(d) 40 %-70℃ (e) 40 %-80℃ (f) 40 %-90℃

(g) 45 %-70℃ (h) 45 %-80℃ (i) 45 %-90℃

**Fig. 9.** Scanning electron microscopic view of surface.

and shows these results.

40wt.%-80℃ condition minimized surface roughness less than a few micrometers. However, considering selectivity and the acceptable deviation of surface roughness, 40wt.%-70℃ condition was chosen as the etching condition for the fabrication of MEMS structures using anisotropic etching.

## V. Conclusion

We estimated the optimal condition for (110) Si anisotropic bulk etching and found it at 40wt.% and 70℃ in a Potassium Hydroxide (KOH) solution. In manufacturing this micro structure, we studied the parameters that affect the completed structure in terms of fabrication and design. Through the estimation of the fabricated structure quality versus mask type, we can choose the most appropriate mask for the fabrication of microstructures on (110) wafers. We estimated the decrement rate of comb length to incorporate it into comb design. 525$\mu m$ height micro comb structures on a (110) silicon wafer were fabricated by anisotropic etching using Potassium Hydroxide etchant.

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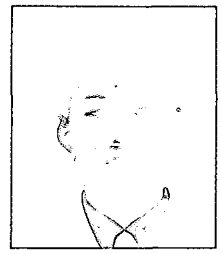

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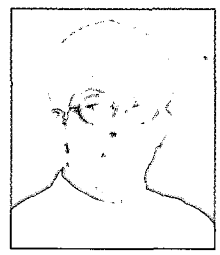

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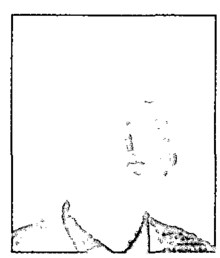

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