Fidelity of Mask Shape and Use of a Correction Method in Anisotropic Si Wet Etching

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Anisotropic wet etching is widely used in MEMS fabrication processes. As this etching has different etching rates for each crystal lattice face, the etched window shape changes during etching. The fidelity of the mask shape is discussed and a correction method is proposed. It was shown that a rectangle tilted 45 degrees to (110) became octagonal and finally rectangular in shape parallel to (110), while a rectangle parallel to (110) maintained its shape. A circle mask shape also became octagonal and then rectangular. It was demonstrated that deviations from the designed shape that occur during the etching can be corrected on the mask shape in advance. This method is useful for the fabrication of circular etched window shapes.

Keywords: Anisotropic etching, MEMS, Si wafer, mask, correction

1. Introduction

Micro-Electro-Mechanical Systems (MEMS) are devices which comprise integrated mechanical parts, electrical parts, sensors and actuators within one chip on a silicon substrate. MEMS is expected to play a key technological role in the development of various devices such as those related to information technology, medical, biotechnology, automobile and robotics given the small chip size and accurate function [1, 2].

Although the manufacturing process of MEMS devices is based on a semiconductor fabrication process, it requires more complicated processes to fabricate the three dimensional structure of a mechanical part.

To date, two etching methods have been employed, and are referred to as dry etching and wet etching. A vacuum system and high electric power system to generate a plasma is required for the dry etching process. On the other hand, the chemical wet etching system is smaller and cheaper compared to the dry system since it only requires the use of a wet etching bath which controls the etching solution concentration and temperature. Both isotropic etching, which utilizes a mixed acid solution of nitric acid and hydrogen fluoride, and anisotropic etching, which utilizes an alkaline solution such as KOH or organic alkaline solution, are available for the wet etching process. Anisotropic wet etching is widely used in MEMS processes to create three dimensional structures since this process can generate anisotropic shapes.

It is known that single-crystal Si has a diamond structure and each crystalline face possesses different etching rates during anisotropic wet etching. The etching rate of all faces except the (111) face is 1~2-fold higher compared to that of the (100) face, while the etching rate of the (111) face is markedly smaller than that of the (100) face. These rates depend on the concentration of the alkaline solution employed since the etching mechanism differs between concentrated and dilute solutions [3, 4].

A schematic view of an etched window shape with anisotropic etching is shown in Fig. 1. The (111) face which is tilted 54.74 degrees is generated since the etching rate of the (111) face is markedly smaller than that of the (100) face in anisotropic wet etching. On the other hand, the
difference in etching rate at each crystal face makes it difficult to achieve a final etching shape which is the same as the etching mask [5].

Figure 2 shows the mask shape and shape generated after etching for different mask shapes. In the case of a rectangular shape with side parallel to (111), the shape achieved after etching maintains the same shape as the original mask. However, in the case of 45 degree rotated rectangular and triangular shapes, new sides parallel to (111) appeared and the final shape differed from the original mask shape. Furthermore, use of a circular shaped mask generated an octagonal shape.

In this paper we investigate the effect of using different mask shapes during anisotropic wet etching and propose a method of mask shape correction to achieve the original design after etching.

2. Experiment
Si (100) substrate possessing a thermal oxide film of 48 nm was used. The oxide film was formed using an electric furnace at 950 degrees. The mask patterns used were printed into Photomask film. Figure 3 shows the process involved for anisotropic etching. The resist film was coated onto a Si substrate containing an oxide layer. The mask patterns were printed into the resist film and then developed using TMAH 2.38% solution. The etching masks of the SiO₂ patterns were fabricated by wet etching using 5% HF solution and followed by resist film removal. Anisotropic wet etching was performed by EPW. The conditions are shown in Table 1.

<table>
<thead>
<tr>
<th>Mask</th>
<th>After Etching</th>
</tr>
</thead>
<tbody>
<tr>
<td>Square</td>
<td><img src="image" alt="Square Mask" /> <img src="image" alt="Square After Etching" /></td>
</tr>
<tr>
<td>Rotated square</td>
<td><img src="image" alt="Rotated Square Mask" /> <img src="image" alt="Rotated Square After Etching" /></td>
</tr>
<tr>
<td>Triangle</td>
<td><img src="image" alt="Triangle Mask" /> <img src="image" alt="Triangle After Etching" /></td>
</tr>
<tr>
<td>Circle</td>
<td><img src="image" alt="Circle Mask" /> <img src="image" alt="Circle After Etching" /></td>
</tr>
</tbody>
</table>

Fig.2. Mask shape and generated shape after etching with different mask shapes.

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<table>
<thead>
<tr>
<th>Etching Solution (EPW)</th>
<th>Ethylenediamine NH₂(CH₂)₂NH₂ 46.4 mol%</th>
<th>Pyrocatechol C₆H₄(OH)₂ 4.0 mol%</th>
<th>DI-water H₂O 49.6 mol%</th>
</tr>
</thead>
<tbody>
<tr>
<td>Temperature</td>
<td>85 °C 5 °C</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Process time</td>
<td>30 – 90 min</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

Table 1 Anisotropic etching conditions using EPW.
3. Results and Discussion

3.1 Rectangular mask

Etched window shapes utilizing a rectangular mask parallel to (110) are shown in Fig. 4 (a). As the mask was parallel to (110), the mask shape was maintained during anisotropic etching. The (111) face was generated at the side of the etching face. Etching was only preceded at the bottom (100) face. Finally, etching should be terminated when the etching depth is equivalent to the length of the side. The (111) face was clearly observed following SEM observation of the etched window, as shown in Fig. 4(a). Top views of the etched window using a rectangular mask tilted 45 degrees to (110) are shown in Fig. 4 (b). The position of the corner was fixed since the (111) face was generated at the corner. As the etching at the side proceeded, the square shape became octagonal. The length of the original mask side decreased while the length of the new side increased during etching. Finally, the etching shape generated should comprise a 45 degrees rotated rectangular shape. The (111) face was observed at the corner and many other faces were observed following SEM observations, as shown in Fig. 4 (b).

The etching depth of (100) and the length of (110) are shown in Fig. 5. It was shown that the (100) and (110) faces possess almost the same etching rate under these etching conditions. As the average etching rate was $0.27 \mu m/min$, 150 $\mu m$ of a rotated square shape shown here should generate 212 $\mu m$ of a rectangular shape with side parallel to (110) after ca. 280 min.

3.2 Circular mask

As previously mentioned, differences appear in the etched shape when a circular mask is employed. Figure 6 shows the circular mask shape and etched window shapes generated at various etching times. It was clearly observed that the etched shape generated changed from circular to octagonal since the (111) face possesses a markedly slower etching rate compared to the other faces.

The etching depth of (100) and length of (110) are shown in Fig. 5. It was shown that the (100) and (110) faces possess almost the same etching rate under these etching conditions. As the average etching rate was $0.27 \mu m/min$, 150 $\mu m$ of a rotated square shape shown here should generate 212 $\mu m$ of a rectangular shape with side parallel to (110) after ca. 280 min.

Figure 7 shows the corner shape generated during etching. Circularity was defined according to the following method to quantitatively evaluate the deviation from the original mask shape. A
circle was inscribed onto the measured etched shape. Distances between the circle and the etched edge for each angle were measured and normalized by the inscribed circle radius. Circularity was defined as the RMS of these differences. For instance, the RMS is 0 for a circle, 0.1216 for a square, and 0.0248 for an octagon.

3.3 Mask shape correction

We attempted to design a mask shape which was corrected based on etching rate differences in order to achieve a truly circular shape after etching. Etching rates were calculated from differences in the mask edge and etched shape at each angle based on the measurement data, and the positions of mask edge were determined using these etching rates. The tangential angle at each position changed slightly during the etching. This effect was not taken into account to simplify the calculation in this evaluation. Figure 10 shows the mask shapes designed using this correction method.

Figure 11 shows a summary of the circularity for the 30 µm etching using the mask corrected for the 18 µm etching. It is clear that the final etching shape improved, even though the total etching was exceeded by 1.5 times.

Figure 12 shows application of the mask shape correction method to other mask designs. It was shown that various concentric circular shapes were
successfully formed. Our results demonstrated that the mask correction method outlined in this report can be utilized for the fabrication of circular shapes with anisotropic etching.

<table>
<thead>
<tr>
<th>No correction</th>
<th>Mask</th>
<th>After etch</th>
<th>Mask</th>
<th>After etch</th>
</tr>
</thead>
<tbody>
<tr>
<td>With correction</td>
<td>Mask</td>
<td>After etch</td>
<td>Mask</td>
<td>After etch</td>
</tr>
</tbody>
</table>

Fig.12 Application of the mask shape correction method.

4. Conclusion
The present study dealt with investigating the fidelity of mask shape during anisotropic wet etching and its correction method. A rectangle tilted 45 degrees to (110) became octagonal with side parallel to (110), and finally became rectangular with side parallel to (110) and with side length equal to the square root of two, while a rectangle parallel to (110) maintained its shape. Use of a circular mask shape also generated an octagonal and then finally a rectangular shape. It was demonstrated that deviations from the designed shape generated during etching could be corrected in advance by altering the mask shape. This method could be utilized for the fabrication of circular etched window shapes.

5. References