Anisotropic Bulk Etching of (110) Silicon with High Aspect Ratio

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Summary

The characteristics of (110) silicon anisotropic bulk etching are studied with varied temperature and concentration of aqueous KOH solution. The etch rates of (110) and (111) planes increase with increasing temperature but decrease with increasing concentration. The maximum etch rate ratio is above 150 at 45 exact wt.% and 60°C of aqueous KOH solution. Surface roughness varies greatly with concentration, and the minimum roughness is observed in an aqueous KOH solution of 41 exact wt.%. In 41 exact wt.% aqueous KOH solution at 65°C, comb structure have been fabricated which are 8 μ m wide, 150 μ m high and separated by 7 μ m gaps, using a comb mask pattern 10 μ m wide with 5 μ m gaps.

KEYWORDS : (110) silicon, anisotropic bulk etching, high aspect ratio, comb structure

1 INTRODUCTION

Anisotropic etching of silicon has become an important technology in silicon processing. Anisotropic etching of single crystal silicon, resulting from different etch rates in each of its crystallographic planes, has been used to fabricate various structures[1,2,3]. The anisotropic etching of (110) silicon provides useful means for the fabrication of high-aspect-ratio structures with atomically smooth, vertical sidewalls because of high etching selectivity between (111) and (110) planes.

Experimental research on (110) silicon anisotropic etching has been widely performed. D.M. Allen[4], P. Krause[5], and Y. Uenishi[6] experimented with holes and narrow groove patterns for (110) silicon etching under certain specific etching conditions, with fixed concentration or temperature. Kishi[7] etched (110) silicon anisotropically with no mask at higher temperature and obtained etch rate, etch rate ratio and surface roughness in various etching condition. K. Sato also studied characteristics of (110) silicon anisotropic etching with hemispherical specimens in aqueous Potassium Hydroxide(KOH) under several different conditions[8,9]. These studies have shown that the anisotropic etching characteristics of (110) silicon vary with concentration, temperature, and shape of the mask pattern. Therefore, there is a need for study of the

etching of (110) silicon with various concentrations, temperatures and patterns.

In this paper, the characteristics of (110) silicon anisotropic bulk etching such as etch rates, etch rate ratio, surface roughness and beam length are studied for fabricating comb structure with varying temperatures, concentrations of KOH aqueous solution and comb dimension. Comb structures with high aspect ratios are fabricated by using conditions that allow high etch rate ratios and smooth etched surface.

2 EXPERIMENT

Using (110) silicon wafer, we deposited 1000 Å thermal oxide to buffer internal stresses between bulk silicon and Si₃N₄ layer, and 3000 Å LPCVD nitride for a masking layer, in KOH aqueous solution. (110) wafers have a primary flat to indicate the <111> direction, but this is accurate to only about $\pm 1^\circ$ along the exact <111> direction. To find the exact <111> direction more exactly, we used a fan-shaped alignment target composed of 8 μ m beams, which is then placed 0.1° between $\pm 4^\circ$ range, and the misalignment between an etch mask and the <111> direction was determined to $\pm 0.05^\circ$ [10]. By aligning comb pattern along this exact <111> direction, a high-aspect-ratio comb structure can be obtained.

The comb shown in Figure 2, 10 μ m and 20 μ m wide, respectively and with 5 μ m gaps, were fabricated to

investigate the etching characteristics. Etching of (110) silicon is performed at temperatures from 60°C to 90°C and concentrations of KOH aqueous solution between 32 exact wt.% and 45 exact wt.%. Exact wt.% is measured by means of neutral titration and the temperature and concentrations are controlled to under 0.5 %.

Figure 1. SEM photograph of alignment target after wet etching

(a) 10 μm width, 5 μm gap (b) 20 μm width, 5 μm gap
Figure 2. Fabricated comb structures with a different width

3 EXPERIMENTAL RESULTS

3.1 Etch Rates of (110) and (111) Plane

Figure 3 and Figure 4 show the etch rate after 100 minutes of (110) plane and (111) plane when (110) silicon bulk etching is performed.

Figure 3. Etch rate of (110) plane

Etch rates of the (110) and (111) planes are

calculated by measuring the height and width of the structure using a laser profiler (KEYENCE VF-7500). The etch rates of both planes increase with increasing temperature, and decrease with increasing concentration of KOH aqueous solution. The temperature of etchant has a strong influence on the relative etch rates of (110) and (111) planes than does concentration of KOH aqueous solution. Figure 5 shows the ratios of etch rates between (110) and (111) planes.

Figure 4. Etch rate of (111) plane

Figure 5. Etch rate ratios between R<110> and R<111>

The etch rate ratio increases with either increasing KOH concentration or decreasing temperature. High etch rate ratios, over 100, are obtained in aqueous solutions of 41 and 45 exact wt.% KOH, at controlled temperature from 60°C to 70°C. The highest etch rate ratio, larger than 150, is observed in the case of 45 exact wt.% KOH aqueous solution at 60°C.

3.2 Surface Roughness of Etched Silicon

The roughness of an etched silicon surface is also important to special applications such as micro mechanical structures or micro optics. They are measured using a laser profiler to study etched surfaces in various conditions of aqueous KOH solution. Figure 6 shows the surface roughness of etched (110) silicon planes with different depth from 100 to 300 μm after 100 minutes etching. The surface roughness was observed to have a minimum at 42 exact wt.% and a maximum at

36 exact wt.% of KOH aqueous solution.

Figure 7 shows the photographs of (110) etched planes at different temperatures and concentrations of KOH aqueous solution.

Figure 6. Surface roughness of (110) etched plane

Figure 7. Photographs of (110) etched planes

Characteristic shapes of etched (110) planes are observed at different KOH concentration. Below 36 exact wt%, etched planes of wave shape are observed, but above 36 exact wt%, hillocks are observed on the (110) etched surface. The surface roughness is larger at high temperatures of etchant.

In all cases, (111) planes are smoother than other planes in SEM photographs as shown in Figure 8.

Figure 8. SEM photographs of (110) and (111) plane after etching

The vertical walls in Figure 8 are (111) plane, and the horizontal surfaces are (110) planes. The figures show that the surface smoothness of the (111) plane is not concerned with the roughness of (110) plane.

3.3 Etch Rate of Comb

In fabricating comb structures, not only height and width but also length of the comb are important. Since the length is determined by etch rate ratio, measurement of the etched beam length is required.

Figure 9 shows the etching mechanisms of beam structure. Performing the (110) Silicon etching with rectangular mask, the convex corners are etched to form two fast etched planes of $Facet_l$ and $Facet_r$, immediately (Figure 9(a)), the two facets meet each other to make triangular etched structure at critical etching time t_0 (Figure 9(b)). We assumed that during the step shown in Figure 9(a), the $Facet_m$ which is perpendicular to the (111) plane has strong influence on the etch rate of beam length. However, in next step, this facet seems to be vanished, and the etch rate of beam length is influenced by two fast etch planes $Facet_l$ and $Facet_r$, respectively (Figure 9(c)).

Figure 9. Etching mechanism of beam structure

Critical etching time t_0 from (a) to (c) can be determined by etch rates of $Facet_l$ and $Facet_r$, as in Eq.(1) and the etch rate of beam is equal to the etch rate of $Facet_m$.

$$t_0 = \frac{W}{(R_l \sec \theta_l + R_r \sec \theta_r + 2 \times R_{111})} \quad \dots (1)$$

where W : Initial width of comb
 R_{111} : Etch rate of (111) plane
 R_l : Etch rate of $Facet_l$
 R_r : Etch rate of $Facet_r$

Therefore the reduced length of beam before t_0 is calculated simply by Eq.(2).

$$L_{Reduced} = R_m \times t \quad \dots (2)$$

where R_m : Etch rate of $Facet_m$
 t : etching time ($< t_0$)

After two facets $Facet_l$ and $Facet_r$ meet each other as shown in Figure 9(b), the remained beam length can be expressed as Eq.(3) and simplified etch rate of beam can be calculated simply as Eq.(4).

$$L_{Reduced} = L_{t_0} + R_{Beam}(t - t_0) \quad \dots (3)$$

$$R_{Beam} = R_{lp} - \frac{\cot \theta_l}{\cot \theta_l + \cot \theta_r} (R_{lp} - R_{rp}) - 2 \times \cot \theta_r \times R_{111} \quad \dots (4)$$

where L_{t_0} is the length of beam at the time t_0

R_{Beam} is the etch rate of beam

$R_{lp} = R_m + R_l \csc \theta_l$

$R_{rp} = R_m + R_r \csc \theta_r$

and R_{lp}, R_{rp} are lengthwise etch rate of beam

Figure 10 shows that the measured length of beam coincides with the calculated value, and the difference of beam length results from the initial etching time which is dependent on the width of comb. However, after initial etching, beams are linearly decreased independent on the comb width. Consequently, as the width of the beam is wider, the remained beam is longer.

Figure 10. Etching of beam(41wt.%, 65°C KOH aqueous solution)

3.4 Fabrication of Comb Structure

With consideration of etching condition such as high etch-rate ratios between $R_{\langle 110 \rangle}$ and $R_{\langle 111 \rangle}$, appropriate etch time, and minimum surface roughness, the etching condition for comb structures was chosen as aqueous KOH solution of 41 exact wt% at 65°C.

During fabrication of comb structures by (110) silicon anisotropic etching, it is observed that if the gap of comb is narrow, then the etch rate of narrow gap is smaller than that of widely opened surfaces as Ohwada reported[11]. The etched depth of narrow gap is about 30 μm shallower than that of the wider one, therefore 30 minutes overetching can make these structures wholly

penetrated.

Using this etching condition, we successfully fabricated comb structures which are 8 μm wide, 150 μm high and with 7 μm gaps using a comb mask pattern of 10 μm width and 5 μm gap(Figure 11.)

Figure 11. Fabricated comb structures. The width is 8 μm, gap is 7 μm and height is about 150 μm

4 CONCLUSION

We have studied the characteristics of (110) silicon anisotropic etching with varying temperature and concentration of aqueous KOH solution. The etch rates of (110) and (111) planes increase with temperature increasing and decrease with the concentration decreasing. High etch rate ratios are observed in KOH solution at low temperature and high concentration. The maximum etch rate ratio is above 150 at 45 exact wt.% and 60°C of aqueous KOH solution. Surface roughness varies greatly with concentration of etchant, and increases with rising temperature. The maximum surface roughness is observed in 36 exact wt.% and the minimum surface roughness in 41 exact wt.% of aqueous KOH solution.

To fabricate comb structure of high-aspect-ratio and smooth surface, we chose 41 exact wt.% KOH solution at 65°C. In these conditions, comb structures have been fabricated 8 μm wide, with 7 μm gaps and 150 μm high, using a comb-shaped mask pattern with lines 10 μm wide and 5 μm apart.

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