Novel Wet Anisotropic Etching Process for the Realization of New Shapes of Silicon MEMS Structures

Prem Pal, Kazuo Sato, Miguel A. Gosalvez, Mitsuhiro Shikida*
Department of Micro and Nano System Engineering, Nagoya University Nagoya
*Laboratory of Physics, Helsinki University of Technology, PO Box 1100, 02015 HUT, Finland
Email: prem@kaz.mech.nagoya-u.ac.jp

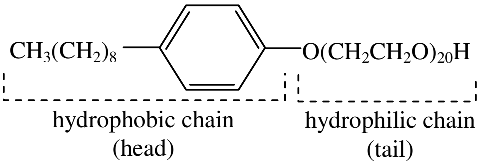
Abstract:

In this work, we have developed a novel anisotropic wet etching process for the fabrication of MEMS microstructures with rounded concave and sharp convex corners, grooves for chip isolation, mesa structures with bent V-grooves, and 45° mirrors by using a single etching mask. Tetra Methyl Ammonium Hydroxide (TMAH) at various concentrations with and without the non-ionic surfactant NC-200 at 0.1% of the total volume of the etchant has been used. In order to fabricate the microstructures with rounded concave corners, round shape mask pattern was used. Mesa structures and grooves for chip isolation were realized using spatially efficient convex corner compensation structures.

1. INTRODUCTION

Silicon wet anisotropic etching is known to be a very economic method in comparison to Deep Reactive Ion Etching (DRIE) for the realization of different kinds of MEMS structures [1-4]. The conventional design of MEMS structures fabricated by wet silicon bulk micromachining on (100)-Si has sharp edge convex and concave corners [2, 5-7]. This design exhibits stress concentration at the concave corners when a load is applied, which may initiate micro-cracks. By providing rounded concave corners instead of sharp ones, the stress can be reduced, improving the mechanical efficiency of the microstructures. In wet anisotropic etching, sharp convex corners are usually fabricated using the corner compensation method [8-18]. In this method, extra features are added at the convex corners to delay the etching. The shape and size of the compensating pattern depend upon the etchant and its concentration, etching depth and temperature. The sharp convex and concave corner in (100) silicon wafer are formed by the intersection of two adjacent {111} planes, while the rounded concave corners are defined by a group of crystallographic planes whose indices vary along the perimeter of the corner. Therefore, it is difficult to apply the corner compensation method for rounded concave corners. Extensive spatial requirements are a major issue in the corner compensation method, especially for the realization of grooves for chip isolation and mesa structures surrounded by bent v-grooves where less space is available than is required for the corner compensating geometry.

In this research we have developed new design methodology and etching solutions to eliminate the high spatial requirements for the convex corner compensation method and to fabricate microstructures with rounded concave and sharp corners. The etching process is developed using TMAH solutions with and without the surfactant NC-200, which contains 100% polyoxethylene-alkyl-phenyl-ether with a hydrophobic head '$CH_3(CH_2)_8$-C_6H_4' and a hydrophilic tail '$O(CH_2CH_2O)_{20}H$'.



2. EXPERIMENTAL WORK

P-type (1-100 Ωcm) Czochralski grown (100)-oriented silicon wafers of three inches in diameter are used. Thermally grown silicon dioxide is used as masking layer. First, the anisotropic etching characteristics, consisting on (1) the etch rate, (2) the etched surface morphology, and (3) the undercutting at convex and rounded concave corners, are evaluated in various concentrations (10, 20 and 25 wt%) of pure and surfactant NC-200 (at 0.1% of the total volume of the etchant) added TMAH solution for the optimization of the etching conditions. The various mask patterns for determining the etching characteristics and for the fabrication of MEMS structures are defined using a standard lithography process followed by silicon dioxide etching. Prior to anisotropic etching, wafers are cleaned properly and dipped in 5% hydrofluoric (HF) acid solution for 1 min. to remove the native oxide followed by through rinsing in de-ionized water.

Various kinds of designs have been proposed for the convex corner compensation structure, as shown in the Fig. 1 [8-18]. These designs are basically developed for pure KOH, TMAH and EDP solutions. In order to fabricate the microstructures with rounded concave and sharp edged convex corners, a round-shaped mask pattern is used at the concave corners and different geometries are studied for the convex corners, as shown in Fig. 1. The dimensions of the compensating structures for various etch depths are

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determined using the experimental etched profiles for the rounded concave and sharp convex corners. Rectangular mask openings, as shown in Fig. 2, are used for the realization of a 45º mirror for optical MEMS applications [19-20]. In this case, the edges of the rectangular strips are aligned along the <100> direction during the lithography process.

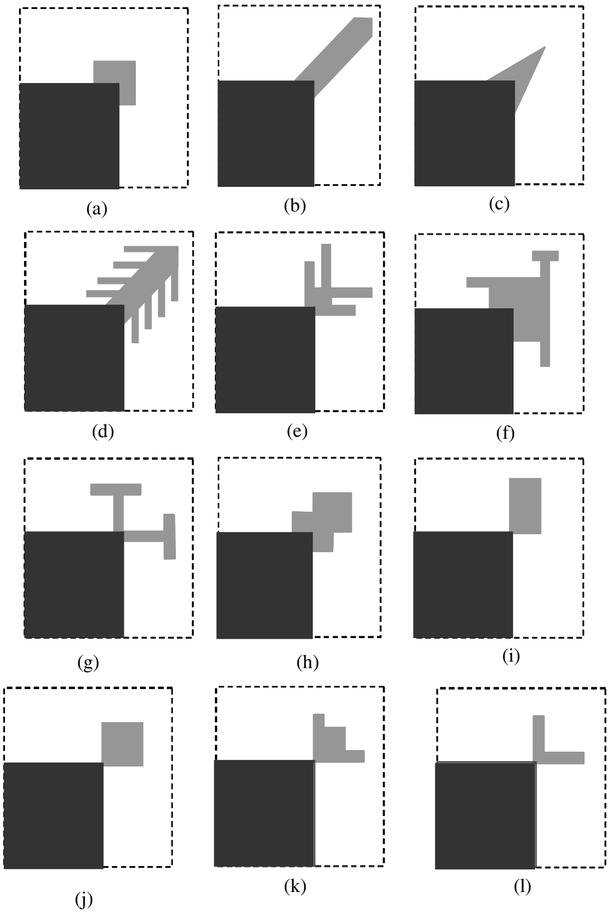


Fig. 1 Different corner compensation designs used to realize convex corners [8-18].

The etch depth is measured using a surface profiler (DEKTAK 3 ST). The dimensions of the etched profile are measured using an optical microscope (OLYMPUS STM6) and the surface roughness is measured by a non-contact 3D optical profiler (ZYGO).

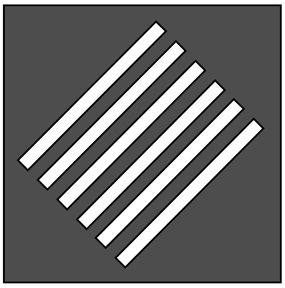


Fig. 2 Schematic view of the mask used for the fabrication of a 45º mirror.

3. RESULTS AND DISCUSSION

Fig. 3 shows the etch rates at various concentrations in pure and NC-200 added TMAH at 60 ºC. The etch rate in the pure solution increases with decreasing concentration. However, the reverse relation is observed in the solution containing NC-200, where the etch rate decreases strongly as the concentration decreases. The etch rate difference at low concentration is significantly high, whereas at high concentration (25 wt%) it is very small.

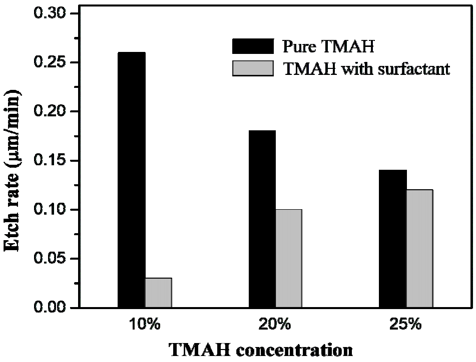
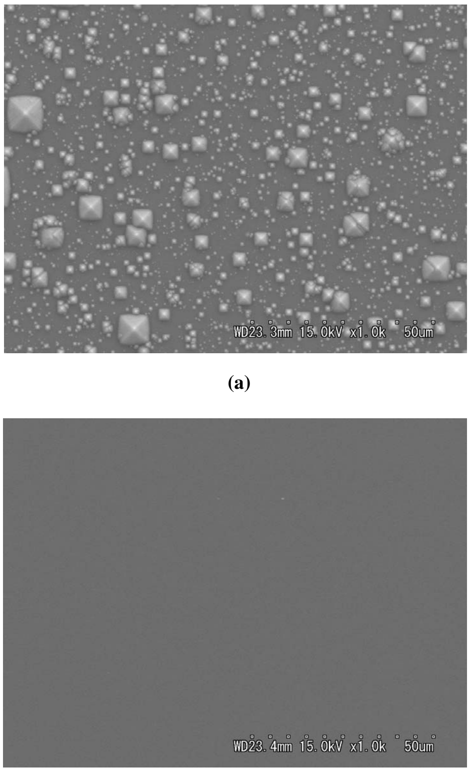


Fig. 3 Etch rate of {100}-Si in pure and NC-200 added TMAH solutions at different concentrations.

Etched surface morphologies in 10 wt% pure and surfactant NC-200 added TMAH are shown in Fig. 4. The average surface roughness at different concentrations in pure and NC-200 solutions is compared in Fig. 5. The addition of NC-200 in TMAH at low concentration (10 wt%) improves the surface morphology dramatically, while at high concentration (25 wt%) it does not affect notably. The etched surface morphology in pure 20 wt% TMAH is very smooth, but exotic results are observed when NC-200 is incorporated. It is found that the surfactant NC-200 in 20 wt% TMAH affects the surface morphology adversely.



(a)

(b)

Fig. 4 SEM photographs of etched surface morphologies in 10 wt% TMAH (a) without and (b) with NC-200.

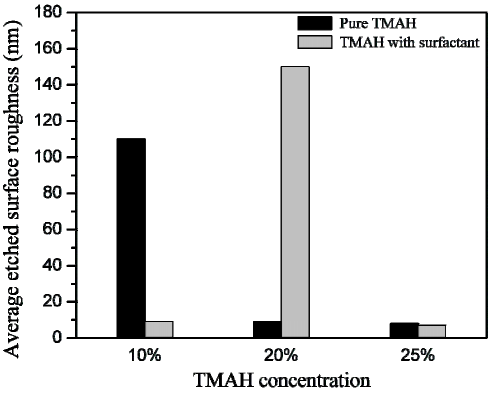


Fig. 5 Comparison of the average etched surface roughness in pure and surfactant NC-200 added TMAH solutions at different concentrations.

A schematic representation of undercutting at rounded concave and sharp convex corners is presented in Fig. 6 together with the definition of the undercutting ratio (l/d). The average corner undercutting ratios 'l_1/d' for the convex corners (as defined in Fig. 6) in pure and NC-200 added TMAH are compared in Fig. 7. The undercutting ratio is reduced significantly at higher concentration, typically to a value of about 92% in 20 and 25 wt%. The same trend is observed in the undercutting ratios 'l_2/d' for the rounded concave corners in pure and NC-200 added TMAH, as shown in Fig. 8. When NC-200 is added to the TMAH solution, the undercutting for both types of corners is measured to be negligible up to an etching depth of 20 µm. The measured results suggest that the 25 wt% TMAH + NC-200 solution is the best choice for the fabrication of new types of MEMS structures because it provides reasonable etch rate with very smooth etched surface finish and reduces the undercutting ratio (*l*/d) to a considerably low level.

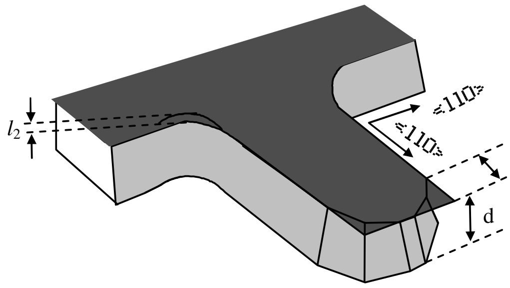


Fig. 6 Schematic representation of corner undercutting and definition of the undercutting ratio (*l*/d).

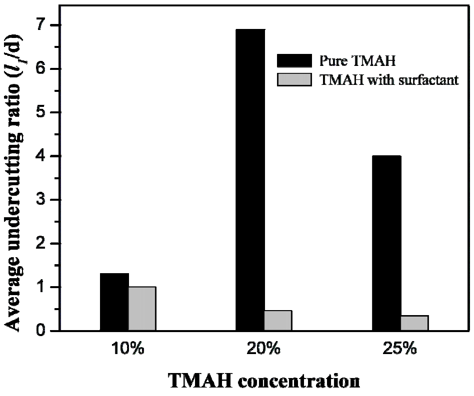


Fig. 7 Average undercutting ratio (l_1/d) at convex corners in pure and NC-200 added TMAH at different concentrations.

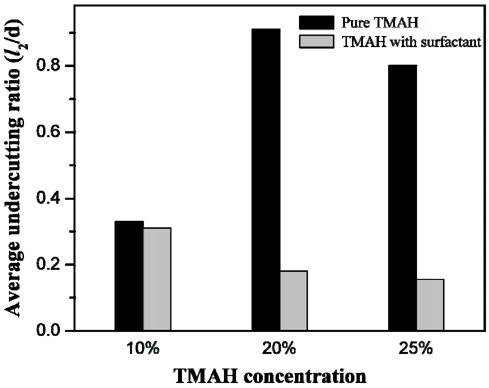
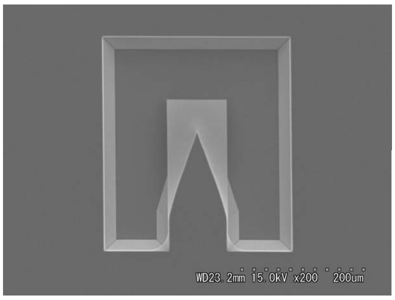
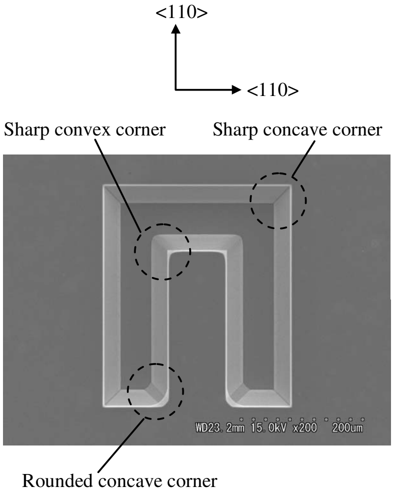


Fig. 8. Comparison of average undercutting ratio (l_2/d) at rounded concave corners in pure and surfactant added TMAH at various concentrations.



(a) Pure TMAH



(b) TMAH + NC-200

Fig. 9. Anisotropically etched cantilever beam shaped patterns with rounded concave and sharp convex corners in 25 wt% TMAH (a) without and (b) with NC-200 (Etching depth = 35 µm). A drastic reduction in the undercutting at both corners is observed when the surfactant is present in the solution.

Fig. 9 shows the SEM pictures of cantilever beam shaped etching pattern with rounded concave and sharp convex corners in pure and NC-200 added TMAH. It is clearly visible that the undercutting at both types of corners is reduced significantly when NC-200 (0.1% of the total volume of the etchant) is added in the TMAH.

The high concentrations of TMAH (20 or 25 wt%) exhibit severe undercutting at convex corners, strongly requiring the design of a corner compensating geometry. In the case of high concentration, a <100> oriented beam compensating structure provides sharp edge convex corners. In this case, the final shape of the convex corner is usually determined by the lateral undercutting of {100} planes which etch with the same rate as that of {100} wafer surface. Even though the undercutting can be minimized by lowering the concentration, thus reducing the spatial requirements for the compensating geometry, the space is not enough for fitting the extra compensating feature in the case of grooves for chip isolation and mesa structures surrounded by bent V-grooves. Since 25 wt% TMAH + NC-200 provides much less undercutting, the design of spatially efficient structures is possible for this choice. For this solution, the <100> oriented beams cannot be used as a compensating structure because {110} planes are developed at the edges of the beam during anisotropic etching. Among the various shaped compensating designs, the triangular pattern is found to be most suitable for NC-200 + 25 wt% TMAH. The successful, drastic size reduction of the compensating mask pattern is due to the reduction in undercutting. This results in a space efficient compensating design.

SEM photographs of grooves formed for chip isolation and mesa structures surrounded by bent V-grooves are shown in Fig. 10 and 11, respectively. The triangular compensating mask shown in Fig. 1(c) has been used for both types of structures. 45° slanted sidewalls suitable for optical mirrors made of {110} crystallographic planes with very smooth surface finish are shown in Fig. 12.

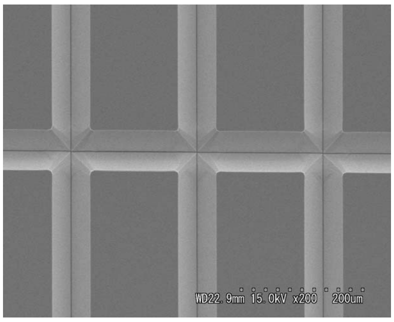


Fig. 10 SEM image of grooves fabricated for chip isolation (etch depth = 50 µm).

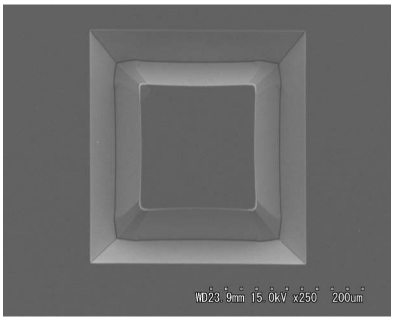


Fig. 11 Mesa structure surrounded by bent V-grooves (etch depth = 50 μm).

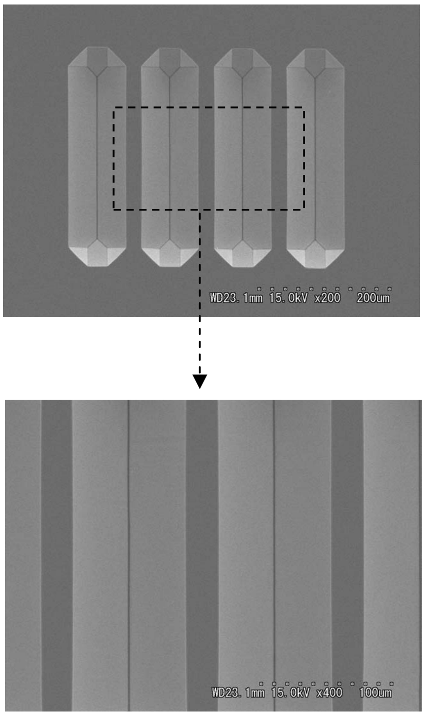


Fig. 12. 45º slanted sidewalls with highly smooth surface finish etched in 25% TMAH + NC-200 (etch depth = 50 μm).

4. CONCLUSION

New design and processes are proposed and demonstrated for the fabrication of different silicon MEMS structures using TMAH solutions containing the surfactant NC-200. The technique is fully compatible with CMOS processing. The etching process was optimized by analyzing the etching characteristics of various concentrations of pure and NC-200 added TMAH solutions. 25 wt% TMAH with NC-200 is an optimal solution for the fabrication of 45º optical mirrors and microstructures with rounded concave and sharp convex corners. The triangular compensating structure is found to be the most appropriate choice for the fabrication of grooves for chip isolation and mesa structures surrounded by bent V-grooves in NC-200 added 25wt % TMAH.

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