AN IMPROVED ANISOTROPIC WET ETCHING PROCESS FOR THE FABRICATION OF SILICON MEMS STRUCTURES USING A SINGLE ETCHING MASK

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ABSTRACT
We have developed an improved anisotropic wet etching process for the fabrication of various silicon microstructures with rounded concave and sharp convex corners, grooves for chip isolation, meandering micro-fluidic channels, mesa structures with bent V-grooves, and 45º mirrors with highly smooth surface finish by using a single etching mask on (100) wafers. In this work, we use a CMOS compatible anisotropic etchant containing tetramethyl ammonium hydroxide (TMAH) and a small amount (0.1% v/v) of a non-ionic surfactant (NC-200), containing 100% polyoxyethylene-alkyl-phenyl-ether. The process has been developed by analyzing the etching characteristics of (100) silicon wafers in pure and surfactant added TMAH.

1. INTRODUCTION
Wet anisotropic etching is extensively employed as a micromachining technology for the production of low cost MEMS components such as cantilever beams, diaphragms, mirrors and numerous other structures in single crystal silicon wafers. The conventional design of MEMS structures fabricated by bulk micromachining on (100) silicon has sharp edge convex and concave corners [1-4]. However, sharp concave corners are generally avoided from a mechanical engineering point of view because they lead to stress concentration when a load is applied, which may initiate micro-cracks. The stress concentration at the sharp convex corners can be reduced by designing them round, as a result improving the mechanical efficiency. However, the fabrication of round-shaped concave corners in commonly used pure anisotropic etchants such as potassium hydroxide water (KOH), ethylenediamine pyrocatechol water (EDP or EPW), tetramethyl ammonium hydroxide (TMAH) is a difficult task due to the presence of severe undercutting [5, 6]. Another issue related to wet etching is the large extent of the spatial structures used for the fabrication of convex corners by the conventional corner compensation method due to the occurrence of fast undercutting at these corners [7]. This spatial requirement is a major concern, especially for the realization of grooves for chip isolation and bent V-grooves where less space is available than is required for the corner compensating geometry. However, the undercutting of the convex corners is a favorable effect for the realization of microstructures using P^+-Si, SiO_2, Si_3N_4 and other materials, where a fast undercutting rate is advantageous for their quick release. Several kinds of ionic and non-ionic surfactants have been reported for the minimization of the undercutting in TMAH solutions [8, 9].

In this research, we have developed new design methodology and etching processes to overcome the aforementioned issues. The process is developed using TMAH with a small amount (0.1% v/v) of non-ionic surfactant NC-200. This additive contains 100% polyoxyethylene-alkyl-phenyl-ether, being composed of a hydrophobic head '$CH_3(CH_2)_8$-C_6H_4' and a hydrophilic tail '$O(CH_2CH_2O)_{20}H$' separated by a benzene ring (C_6H_{12}). Different MEMS structures with rounded concave and sharp convex corners, curved micro-fluidic channels, grooves for chip isolation, mesas surrounded by bent V-grooves and a 45º mirror with highly smooth surfaces are fabricated using the proposed process.

2. MASK DESIGN
The feasibility of a desired shape of a microstructure on any kind of silicon wafer (e.g. (111), (110), or (100)) is determined by studying the etched profile of various shapes of masking patterns on the respective wafers. This paper deals with microstructures on Si(100) wafers. In order to design the compensating pattern for the realization of convex corners, the identification of the undercutting planes, their etch rates and their angles are required.

Round shape masks were designed for the fabrication of rounded concave corners, whereas several kinds of compensating geometries at the convex corners were tested, including a <100> oriented beam, square and triangular shapes, as illustrated in figure 1. These are used for the realization of grooves for chip isolation, and mesa structures that are framed around by V-grooves. For the production of 45º mirrors with highly smooth surfaces for optical MEMS applications, rectangular mask openings aligned along the <100> direction were used.

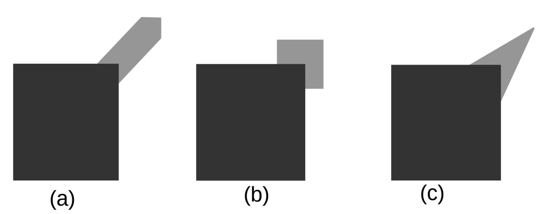


Figure 1: Schematic representation of corner compensation structures tested for the realization of grooves for chip isolation and mesa structures with bent V-grooves in TMAH + NC-200.

3. EXPERIMENTAL METHOD
CZ grown (100)-oriented p-doped silicon wafers of resistivity 1-100 Ωcm were used. Thermal oxidation was used for the formation of the oxide. The oxidized wafers were patterned

using a standard photolithography process followed by oxide etching in buffered hydrofluoric (BHF) acid. Thereafter, the wafers were cleaned properly. Just prior to anisotropic etching, the wafers were dipped in 5% hydrofluoric solution to ensure that there should be no native oxide left on the silicon surface. This step is followed by a thorough rinse in de-ionized water. A circular container made of Teflon was used for the etching experiments. It was equipped with a reflux condenser to maintain the etching concentration. Anisotropic etching was carried out at 60 ºC in pure and NC-200 added TMAH at different concentrations (10, 20 and 25 wt% TMAH). The surfactant was added at a concentration of 0.1% of the total volume of the resulting etchant (0.1% v/v).

We evaluated the etching characteristics, such as (1) the etch rate, (2) the etched surface morphology, and (3) the amount of undercutting at the sharp convex and rounded concave corners, in both pure and TMAH + NC-200. The etch depth was measured using a surface profiler (DEKTAK 3 ST). The dimensions of the etched profile were measured using an optical microscope (OLYMPUS STM6) fitted with an angular and linear dimensions measurement system. The surface roughness was measured with a non-contact 3D optical profiler (ZYGO).

4. RESULTS AND DISCUSSION

The eth rates measured in pure and NC-200 added TMAH are shown in Fig. 2. When NC-200 is added in TMAH, the etch rate is reduced to a considerably low level at low concentration (10 wt%), while at high concentration (25 wt%) it is not affected significantly. In pure TMAH, the average etched surface roughness of {100} increases with decreasing concentration of the etchant. The etched surface morphology is very smooth at high concentration, whereas it is full of hillocks at low concentration, as shown in Fig. 3. The incorporation of NC-200 improves the surface morphology dramatically at low concentration

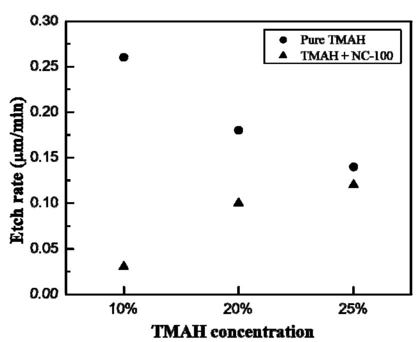


Figure 2: Etch rates in different concentrations of TMAH with and without NC-200.

by preventing the formation of hillocks. At high concentration, it does not affect notably.

Micromasking by hydrogen bubbles generated during the etching process is one of the major factors for worsening the smoothness of a wet etched surface. The stability of hydrogen bubbles on the silicon surface depends upon the etchant's droplet angle (or

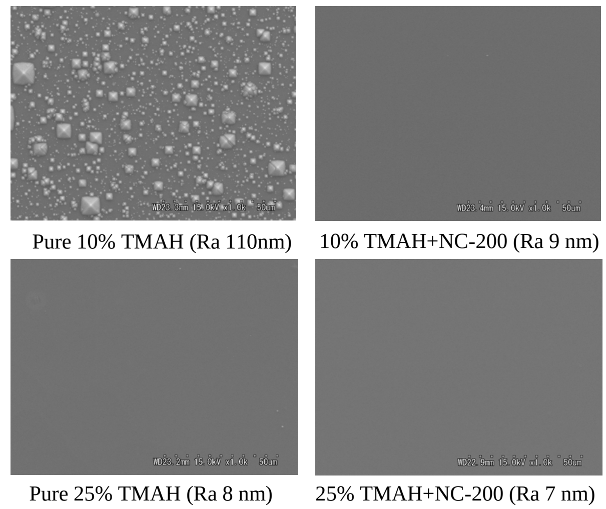


Figure 3: SEM photographs of etched surface morphologies in different concentrations of TMAH without and with NC-200.

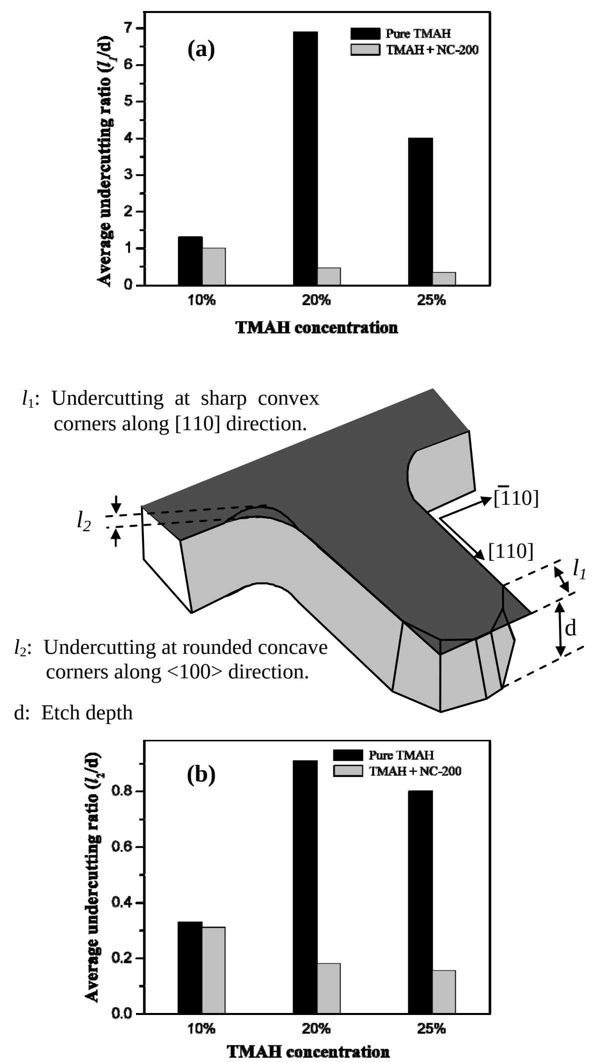


Figure 4: Comparison of average undercutting ratio (l/d) (a) at convex (b) at rounded concave corners in pure and surfactant added TMAH at various concentrations.

wettability/surface-tension of the etchant) [9]. The SEM pictures of the etched surfaces indicate that the addition of NC-200 decreases the contact angle (or increases the wettability) and thus improves the roughness. The average corner undercutting ratios, 'l_1/d' for convex corners and 'l_2/d' for rounded concave corners (as defined in figure 4), are compared in figures 4 (a) and (b), respectively. The undercutting ratio at both types of corners is reduced significantly at higher concentration, with a value of about 92% in 20 and 25 wt%.

If one is required to fabricate square shaped cavities with smooth surfaces and/or to release the microstructures made of dielectrics (e.g. SiO_2, Si_3N_4) or metals (e.g. Cr, Au) by wet anisotropic etching using TMAH, a high concentration of 20 or 25 wt % is recommended as it provides negligible undercutting at concave corners and severe at convex corners. On the other hand, in order to achieve minimum undercutting by preserving the smooth surfaces and a reasonable etch rate for the fabrication of microstructures with rounded and sharp convex corners, 25 wt% TMAH + NC-200 is the most favorable choice.

Figure 5 shows a 35 µm deep T-shaped cantilever beam etched using a mask pattern with rounded concave and sharp convex corners. The structure has been realized in 0.1% v/v NC-200 added 25 wt% TMAH without any corner compensating geometry. It can be seen in the picture that undercutting at both corner types is negligible. The undercutting at rounded concave corners proceeds maintaining the roundness. In order to stress this feature further, the realization of a microstructure consisting on a rounded, meandering channel is shown in figure 6. These channels in wet anisotropic etching are only possible if the undercutting at rounded concave corners is suppressed significantly in comparison to the etch rate of {100} silicon planes.

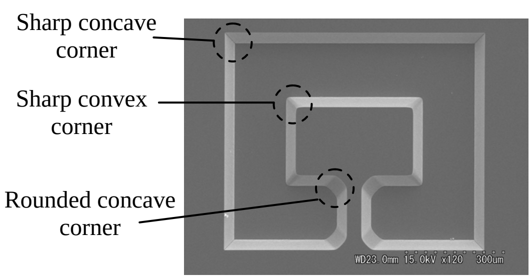


Figure 5: SEM picture of a T-shaped cantilever beam with rounded concave and sharp convex corners fabricated in 25 wt% TMAH + NC-200 without any compensating structure (etch depth = 35 µm).

Although the undercutting at the convex corners in TMAH + NC-200 is reduced drastically and the microstructures of small thickness (about 20 µm) can be fabricated with negligible undercutting, etching for prolonged times to obtain thicker structures (such as mesas and inertial masses) will lead to certain amounts of underetching at those corners. In this case, small, spatially-efficient corner compensation designs can be used, with the basic shapes shown in figure 1. One has to keep in mind, however, that the size of the compensating structures is greatly exaggerated in the figure. In this work, these designs have been used for the realization of grooves for chip isolation and mesa structures with bent V-grooves.

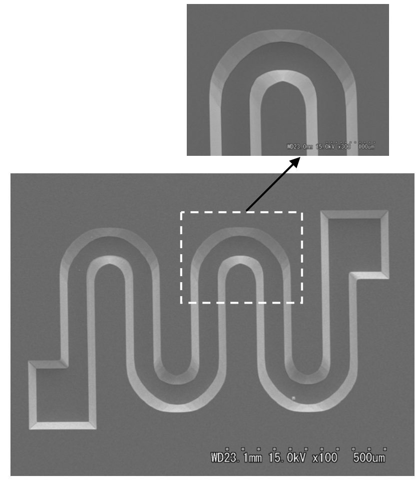


Figure 6: Micro-fluidic channel obtained in 25 wt% TMAH + NC-200 (etch depth = 30 µm).

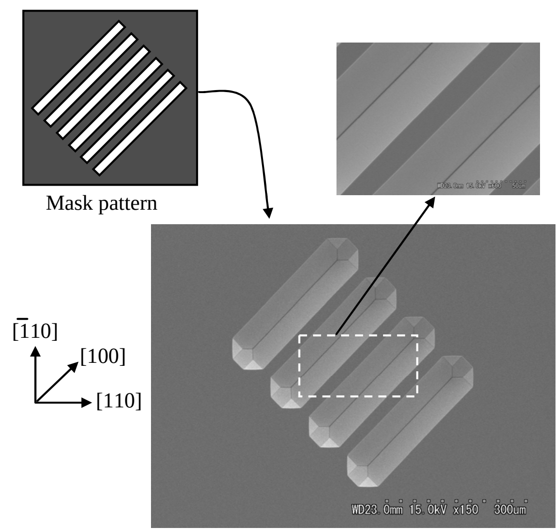


Figure 7: 45º mirror with highly smooth surface finish (groove's depth = 50 µm)

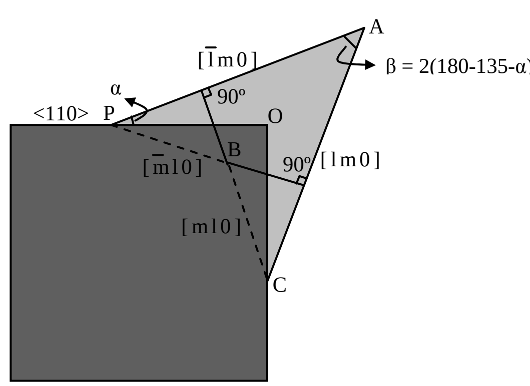
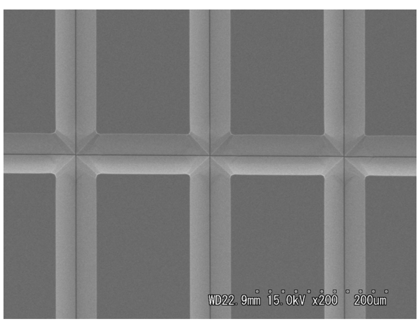


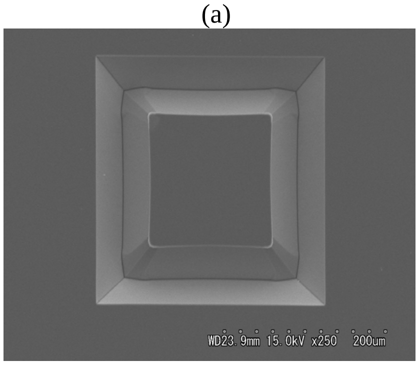
Figure 8: Schematic representation of design methodology used for triangular shaped corner compensation structure.

The <110> oriented beam of figure 1(a) is known to give very sharp edge convex corners in pure KOH and TMAH solutions. However, when it is used as the compensating structure in TMAH + NC-200, {110} planes are developed at the long edges of the beam because these planes have very slow etch rate in comparison to {100}. Therefore, this design cannot be used in this solution for the fabrication of sharp convex corners. This is, however, beneficial for the fabrication of grooves bounded by {110} crystallographic planes with highly smooth surface finish, as shown in figure 7. The sides of the grooves make an angle of 45º with the {100} wafer surface. The grooves are used as optical fiber guides and as 45º mirrors, coupling out the light at 90º with respect to the wafer surface [4, 10].

In a similar manner, the corner compensation design shown in figure 1(b) was also found to be ineffective for the realization of sharp convex corners in the proposed etchant. However, the triangular structure shown in figure 1(c) is very appropriate. The design parameters for this type of compensating pattern are illustrated in figure 8. In order to design a triangular compensating structure, it is essential to determine the angle formed by the edges of the mesa (<110> directions) and the intersecting lines (PB, CB) of the beveling planes and wafer surface (i.e. $\angle OPB = \angle OCB = \angle APO = \angle ACO = \alpha$). In our experiment, α was measured to be 18±2º. The sides of the triangle are determined using the convex corner undercutting ratio (l_1/d). Since the undercutting ratio is significantly reduced, the triangular structure is very small and can be easily fitted in the reduced space available around the convex corners. As an example, grooves for chip isolation and mesa structures surrounded by bent V-grooves fabricated using the triangular compensating geometry are shown in figures 9 (a) and (b), respectively.



(a)



(b)

Figure 9: SEM pictures of microstructures in 25 wt% TMAH + NC-200: (a) Grooves for chip isolation, (b) Mesa surrounded by bent V-grooves. Both have been realized using the compensating geometry shown in Fig. 1(c). (Etch depth = 50 µm.)

5. CONCLUSION

The etching characteristics of pure and surfactant NC-200 added TMAH solution are studied for the fabrication of various kinds of silicon MEMS structures. 25 wt% TMAH with 0.1% v/v NC-200 provides smooth surfaces, a reasonable etch rate for (100) and minimum undercutting at all types of corners. These properties are beneficially used for the fabrication of microstructures with rounded concave corners, including meandering microchannels and stress-reduced cantilever joints, as well as 45º mirrors for optical applications. Simultaneously, this etchant enables the design of spatially efficient compensating structures in order to fabricate grooves for chip isolation and mesa structures surrounded by bent V-grooves.

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