<310> TRINGULAR CORNER COMPENSATION AND ETCH FLOW MECHANISM FOR ANISOTROPIC TMAH ETCHING OF (100) SILICON

R. Mukhiya
MEMS & Microsensors
CSIR-Central Electronics
Engineering Research Institute (CEERI)
Pilani - 333031 (Raj.), India
rmukhiya@ceeri.ernet.in

Ram Gopal
MEMS & Microsensors
CSIR-Central Electronics
Engineering Research Institute (CEERI)
Pilani - 333031 (Raj.), India

V. K. Khanna
MEMS & Microsensors
CSIR-Central Electronics
Engineering Research Institute (CEERI)
Pilani - 333031 (Raj.), India

T. K. Bhattacharya
Microelectronics & MEMS Laboratory
Electronics & ECE Department
Indian Institute of Technology
Kharagpur -721302 (WB), India

Abstract

Anisotropic wet chemical bulk-micromachining is a simple and cost-effective method for fabricating silicon microsensors. In anisotropic etching, convex corners are attacked; therefore, a proper compensating structure design is often required when fabricating microstructures with sharp corners (convex corners). In the present work, <310> triangular compensation structures have been used for convex corner compensation with 25% wt. TMAH-water solution at 90±1^{0}C temperature. Design and etch flow morphology of the compensating structure is presented. This type of compensation is useful for the applications like microcantilevers, where protection of convex corner is required and space is not a constraint. For 25% wt. TMAH-water solution, it was observed that throughout the etching, {311} planes were responsible for etching in all the directions and no other planes were observed. Etch-front-attack angle remains the same as that of <310> angle. This compensation can give perfect convex corner and mesa, but requires more space. The compensation structure is simple to design and analyze among all other types such as <110> square, <100> bars, and <110> bars of compensating structures.

Keywords:- Corner Compensation (CC), Anisotropic TMAH etching, Bulk-micromachining.

I. INTRODUCTION

In general, convex corner structures and non {111} crystal planes are undercut during wet anisotropic etching [1, 2]. These characteristics have been extensively exploited to fabricate freely suspended microstructures. On the other hand, these effects have to be reduced or prevented in various applications, where structures with convex corners are desired. Experimental study has been successfully carried out to protect convex corners and non {111} crystal planes from undercutting for KOH etching [3-6]. To preserve the shape of convex corners when etching in anisotropic etchants, corner compensation structures have to be used. The etching of convex corners is due to the fact that some planes etch faster than others, resulting in a loss of the desired structure [2, 3]. Addition of extra structures at these convex corners, which will be removed during etching, results in the desired convex corners.

Most of the early works on the corner compensation were mainly related to the anisotropic KOH etching for which undercutting facets have been identified as {411} planes [4]. Square patterns or combinations of square or rectangular patterns are superimposed on the convex corners on the mask for compensation [7, 8]. Another straightforward compensation is triangular structure added to the convex corner, in which angles are bounded by lines in <310> directions [9]. The area required for this compensation is largest [7]. Other compensation structures involve adding <100> bars to the convex corners [4-6]. Though, these <100> bar structures give perfect convex corners, the space requirement is more than the square compensation [7, 10]. In many applications, where perfect convex corners are not required and space is limited, square compensation structure is suitable. Some other structures are also reported in which many <110> strips are added to protect the convex corner [8]. These types of structures are not practical as they leave undesired masses and imprint on the bottom. Among the many etchants tetra methyl ammonium hydroxide (TMAH)-based solutions are the only solution which offers CMOS compatibility and less toxicity [11]. However, pure TMAH shows a very high undercutting ratio. In this paper, analysis and feasibility of <310> triangular compensation structure, as shown in

Figure 1, for CMOS compatible TMAH-water etchant, have been investigated, which is easy to design and analyze. The vertex of the triangle is in <100> direction and sides are in [310] direction, which make an angle of ~18.5° with [110] direction of the mesa. Based on the experimental results and analysis, empirical design equations are formulated.

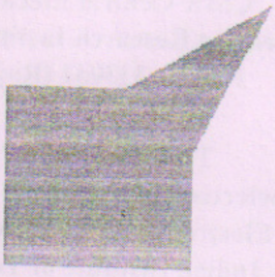


Fig. 1. Mask for mesa type structure with <310> triangular compensation.

II. EXPERIMENTAL DETAILS AND MORPHOLOGICAL STUDIES

In our experiments, 4-inch diameter n-type (100) silicon wafers with resistivity of 8-10 Ω-cm and 500±25 μm thickness were used. Thermally grown silicon dioxide of 1 μm thickness was used as etch mask. Convex square mask with edges aligned to <110> wafer flat were defined on this thermally grown SiO_2 layer with <310> triangular compensation structure, as shown in Figure 2. Wagon-wheel based structure was used for accurate alignment of the structure edge to <110> of the wafer. Thermally grown SiO_2 masking layer was preferred over PECVD Si_3N_4 because of its good adhesion and compressive nature of stress which helps to minimize shape deterioration and deformation near the convex corner of mask [12]. Commercially available Honeywell's 25% wt. TMAH solutions were used in our experiments. 25% wt. TMAH was used to achieve hillock-free smooth surface [11]. All experiments were carried out at 90±1°C temperature in a constant temperature bath without stirring. Constant 25% wt. TMAH concentration was maintained by frequently adding suitable amount of water. Compensation structure was designed for TMAH anisotropic etching based on <310> triangular corner compensation used for KOH anisotropic etching [7, 9]. Dimensions of <310> triangular compensation structure (Figure 2) used in experiments were: length L = 1920 μm, and width W = 2715 μm. During the experiments, etch depth was measured mechanically using a digital micrometer with an accuracy of ±2 μm. Process parameters during the experiments were:

- etch rate of (100) plane R(100) = 0.67 μm/min,
- anisotropic ratio R(311)/R(100) = 2.23,
- anisotropic ratio R(111)/R(100) = 0.071,
- minimal side separation width W_s = 10 μm.

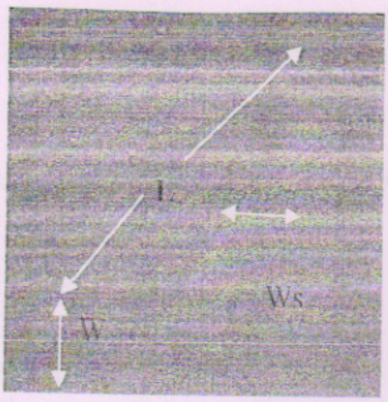
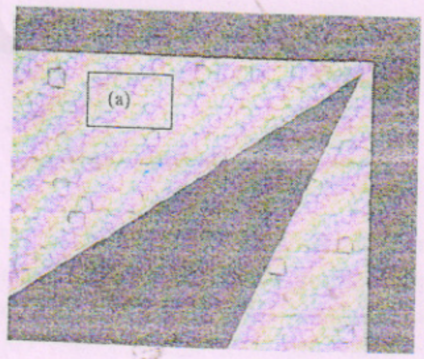
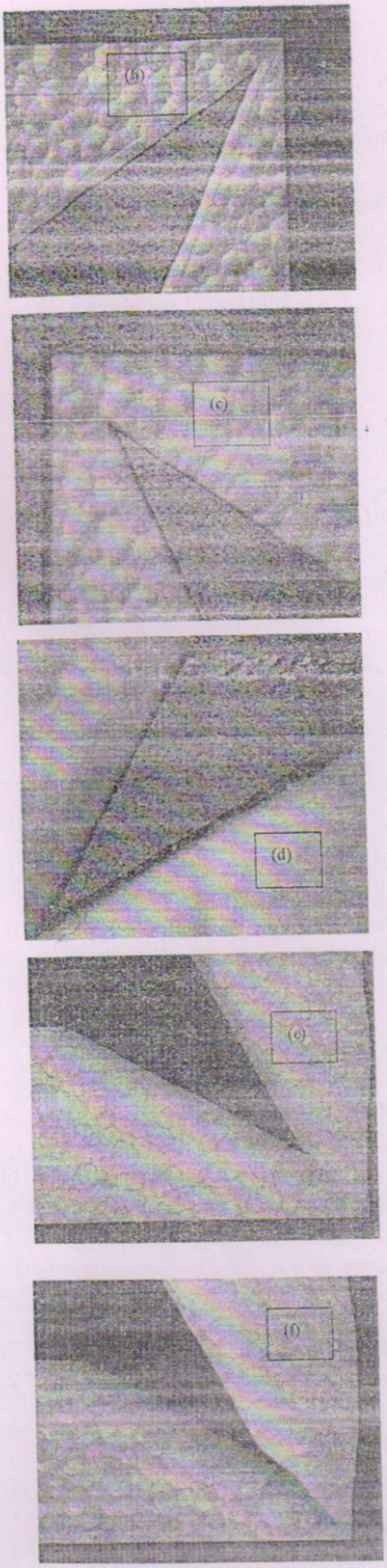


Fig. 2. <310> Triangular corner compensation structure patterned on silicon (100).

To understand the etch flow mechanism and profile, samples were taken out of the etching solution, cleaned and examined. Etching mechanisms around the (111) planes are different in KOH and TMAH solutions [14]. Etch flow profile of <310> triangular compensation structures for TMAH is same as that of for KOH except for etch-front-attack angle, maximum etch rate direction and the difference in anisotropic ratios [4, 6, 14, 15]. The etch attack angles were measured to be 24°-25°, which is the propagation direction of the etch front and determined using a square mask aligned to <110> without any compensation structure, which is in agreement with the reported work [14, 15]. For KOH, {411} planes are responsible for convex corner undercutting [4], while in TMAH {311} planes are responsible [14, 15]. Stepped etching morphology of the compensation structure is shown in Figure 3 for different etch depths. The structure is undercut in TMAH along the two sides in <310> directions. Etch flow is symmetric along both the sides of the triangle. It is observed and verified that this compensation structure is suitable to obtain perfect top-to-bottom convex corner.





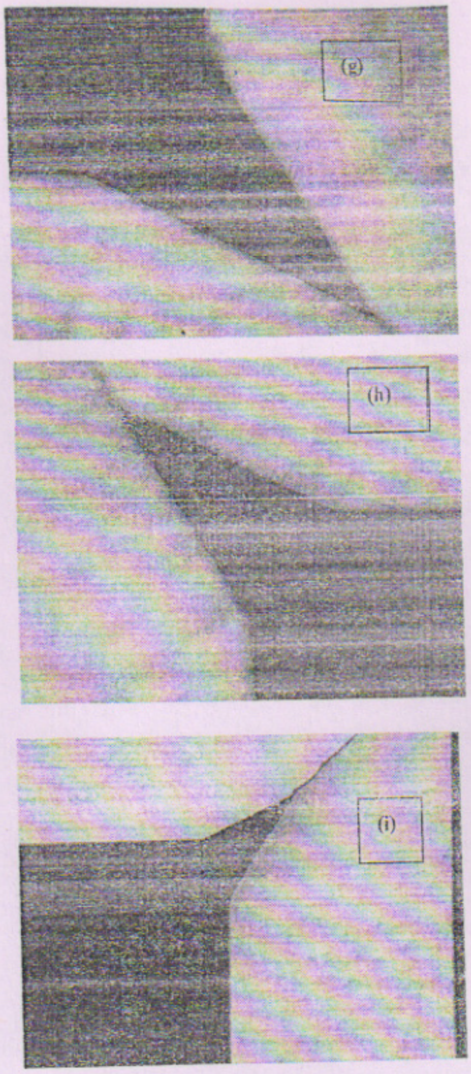


Fig. 3. Etch flow morphology of the compensating structure.

III. RESULTS AND DISCUSSION

As shown in Figure 3, <310> compensation structure gives well-defined and uniform under etch throughout the etching to protect convex corner at the mesa structure attached to membrane. It is clear from the experiments that with this compensation structure, mass and corner can be protected perfectly at the same time, but it leaves large area of the mass attached to the bulk. Based on experiments and analysis, basic design equations (empirical) have been formulated and given by

$$L = 3 D_e \quad (1)$$

$$W = 1.414 L \quad (2)$$

where, D_e is the etch depth and all other symbols have same meaning as given in Section 2.

IV. CONCLUSION

Convex corner undercut during wet anisotropic etching of (100) silicon is a well-known problem. In this paper, <310> square compensation structure has been investigated for CMOS compatible TMAH wet anisotropic etching. Based on experiments and analysis, general design equations have been formulated. {311} planes are found to be responsible for fast etching at the convex corners. It is not the space efficient compensation but gives perfect convex corners with well-defined etch profile and same for other anisotropic etchants as EDP, KOH and Hydrazine [7-9]. Etching morphology is also presented in Section 2, which is similar to that of other anisotropic etchants.

V. ACKNOWLEDGMENT

Authors acknowledge the support of scientific and technical staff of Microelectronic and MEMS Laboratory of E & ECE Dept., of IIT, Kharagpur, while conducting the experiments. Authors also acknowledge the financial support of ISRO, DRDO, DST and CSIR for MEMS technology development through different research projects.

VI. REFERENCES

[1] Seidel H, "The mechanism of anisotropic silicon etching and its relevance for micromachining", *Technical digest of Transducers' 87*, Tokya, Japan, pp 120-25, 1987.

[2] Koide A, Sato K and Tanaka S, "Simulation of two-dimensional etch profile of silicon during orientation-dependent anisotropic etching", *Proc. of the IEEE Micro-electro-Mechanical Systems (MEMS) Workshop*, Nara, Japan, pp 216-20, 1991.

[3] Offereins H L, Kuhl K and Sandmaier H, "Methods for fabrication of convex corners in anisotropic etching of (100) silicon in aqueous KOH", *J. Sens. Actuators A*, vol. 25, pp 9-13, 1990.

[4] Mayer G K, Offereings H L, Sandmaier H and Kuhl K, "Fabrication of non-underetched convex corner in anisotropic etching of (100) silicon in aqueous KOH with respect to novel micromechanical elements", *J. Electrochem. Soc.*, vol. 137, pp 3947-51, 1990.

[5] Enoksson P, "New structure for corner compensation in anisotropic KOH etching", *J. Micromech. Microeng.*, vol. 7, pp 141-44, 1997.

[6] Zhang Q, Liu L and Li Z, "A new approach to convex corner compensation for anisotropic etching of (100) Si in KOH" *J. Sens. Actuators A*, vol. 56, pp 251-54, 1996.

[7] Puers B and Sansen W, "Compensation structures for convex corner micromachining in silicon", *J. Sens. Actuators A*, vol. 21-23, pp 1036-41, 1990.

[8] Bao M, Burrer C, Esteve J, Bausells J and Marco S, "Etching front control of <110> strips for corner compensation", J. Sens. Actuators A, vol. 37-38, pp 727-32, 1993.

[9] Wu X P and Ko W H, "Compensating corner undercutting in anisotropic etching of (100) silicon", *J. Sens. Actuators*, vol. 18, pp 207-15, 1989.

[10] R Mukhiya, A Bagolini, B Margesin, M Zen and S Kal, "<100> bar corner compensation for CMOS compatible anisotropic TMAH etching", *J. Micromech. and Microengg.*, vol. 16, pp 1049-52, 2006.

[11] Tellier C R and Charbonnieras A R, "Characterization of the anisotropic chemical attack of (hhl) silicon plates in a TMAH 25% wt. solution: micromachining and adequacy of the dissolution slowness surface", *J. Sens. Actuators A*, vol. 105, pp 62-75, 2003.

[12] Takao H, Yong C, Rajanna K and Ishida M, "Shape deterioration of mesa structures in post-CMOS anisotropic etching of silicon microstructures: an experimental study" J. Sens. Actuators A, vol. 86, pp 115-21, 2000.

[13] Y Matsumoto, A Okada, K Kawai, H Takao, H D Seo, and T Nakamura, "A study on etching process of glass and and silicon for acceleromater fabrication", *IEEE Digest of Technical Meeting on Sensor Technology, ST-94-6*, Japan, 207-15, 1994.

[14] Trieu H K and Mokwa W, "A generalized model describing corner undercutting by the experimental analysis of TMAH/IPA", *J. Micromech. Microeng.*, vol. 8, pp 80-83, 1998.

[15] Shikida M, Sato K, Tokoro K and Uchikawa D, "Differences in anisotropic etching of KOH and TMAH solutions", J. Sens. Actuators A 80 179-188, 2000.