A measurement free pre-etched pattern to identify the <110> directions on Si{110} wafer

S.S. Singh[1*], V.N. Avvaru[2], S. Veerla[2], A.K. Pandey[1] and P. Pal[2*]

[1]Department of Mechanical and Aerospace Engineering
[2]Department of Physics
Indian Institute of Technology Hyderabad India

*Email- me11b028@iith.ac.in, prem@iith.ac.in

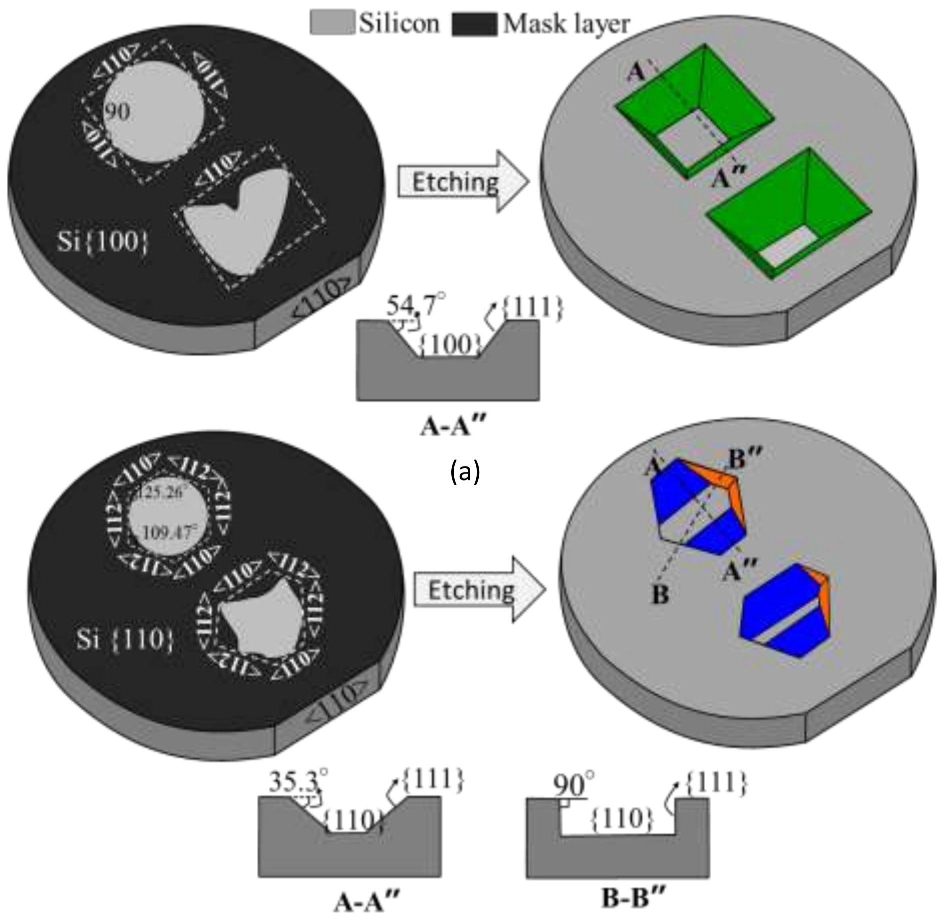
This is the authors' copy of accepted form of the paper
http://dx.doi.org/10.1007/s00542-016-2984-2 .

Abstract

In this paper, we present a self-aligning pre-etched pattern based technique to precisely determine the <110> direction on Si{110} wafer surface. These patterns after etching, reveals the crystallographic direction by self-aligning itself in a straight line at the <110> direction while getting self-misaligned at other directions. As a result, the exact direction can be identified by a simple visual inspection under a microscope without the need of measurement of any kind. To test the accuracy of the proposed method, we fabricated two 32 mm long channels, one oriented along the <110> direction and other along the <112> directions using the <110> direction obtained from the proposed method as the reference. The undercutting is measured at different locations on the two channels and is found to vary within a submicron range in each case. Such uniform undercutting implies that the presented technique to determine the <110> direction is accurate. This methodology is simple and can be used conveniently to fabricate MEMS structures with high dimensional accuracy.

1. Introduction

Wet anisotropic etching is a very popular and well established technique in silicon bulk micromachining [1-16]. It is widely used in the fabrication of MEMS structures with slanted as well as vertical sidewalls [17-27]. At the same time it is inevitable for the realization of freestanding structures for different applications [27-32]. Silicon wafers with principle orientations like Si{100} Si{110} and Si{111} are commercially used for the fabrication of various MEMS structures. On Si{100} wafer, etching of any arbitrary shaped mask opening results in a <110> bounded rectangular V-groove comprising of {111} sidewalls inclined at an angle of 54.7^o to the wafer surface as shown in Fig. 1(a) [33]. However, on Si{110} wafer, etching of any arbitrary shaped mask opening results in a hexagon comprising of 2 slanted {111} plane at the <110> direction inclined at angle of 35.3^o to the wafer surface and 4 perpendicular {111} planes at <112> directions as shown in Fig. 1(b) [34]. As a result, Si{110} wafer is widely used and is inevitable in order to fabricate microstructures with vertical sidewalls using wet chemical bulk micromachining [22, 23, 35-39].



(b)

Fig. 1: Schematic diagram showing the etched profiles on (a) Si{100} and (b) Si{110} wafers.

In wet anisotropic etching, least undercutting takes place at the mask edges comprising {111} planes, for instance <110> direction on Si{100} wafer and both <110> and <112> direction on Si{110} wafer [1, 9, 28, 39, 40]. If the structure needs to be formed by {111} planes, the mask edges must be aligned along the edges containing {111} planes. Therefore, in order to ensure that the fabricated microstructures are dimensionally accurate, it is vital to ensure accurate alignment of mask edges along the crystallographic directions. As a result, precise identification of crystallographic direction is the first and the most useful step in the fabrication of microstructures. Although the wafer flat is usually used as the reference direction, however, the wafer flat itself is usually misaligned by $\pm 1^{o}$. As a result, the wafer flat cannot be used as the reference direction in devices where high dimensional accuracy is required. This necessitates the development of alternate techniques to determine the crystallographic directions accurately. One method is the use of x-ray diffraction which can precisely determine the crystallographic directions. However, the constraint associated with the mounting of x-ray diffraction setup on a mask aligner inhibits its use. Another most widely used technique is the etching of pre-etched patterns prior to the fabrication of required structures [41-48]. In this technique, patterns of various shapes are initially fabricated on the periphery of the wafer and the undercut lengths of the etched structures are used to determine the correct crystallographic directions. Using this technique the crystallographic directions can be identified with high accuracy.

Researchers have proposed various pre-etched patterns to determine the crystallographic directions on Si{100} wafer. However, very few patterns and techniques have been reported to determine the principle directions on Si{110} wafer. Earlier attempts to determine the <110> direction on Si{110} wafer was done by Ciarlo where he used rectangular openings arranged at an angular period [41]. After etching, the rectangular opening with a minimum lateral etch is selected and is least misaligned with the precise <110> direction. However, the task of selecting the structure with small underetch length under a microscope is prone to error. Therefore, for better accuracy the underetch length can be measured to determine the structure with minimum underetch. However it is a tedious task and requires sophisticated equipment to measure such submicron underetch lengths. In another work, James *et al* proposed the fabrication of a single circle of 1 mm diameter as a pre-etched pattern [42]. After etching, the circle takes the shape of a hexagon. The edges of this hexagon are then aligned with a dimensionally similar hexagon on the subsequent mask which contains the required structures fabricated with respect to the edges of the hexagons. While this method does not require measurement of any kind, however it is prone to theta error. Tseng and Chang proposed a method to determine the <100> direction on Si{110} wafer using the deviation of corners of adjacent hexagons as the parameter [43]. At the same time, there have been a few attempts to identify the principle directions on Si{100} wafer as well [44-47]. Most of these methods require some sort of measurement of small undercut lengths for determining the crystallographic directions with high accuracy, which makes it tedious as well as prone to errors.

In this paper, we present a novel methodology using the pre-etched patterns which can precisely indicate the <110> direction without the need of any measurement of any kind. The patterns tend to align itself at the <110> direction making the direction identification quite obvious. At directions away from the <110> direction, these patterns distorts the alignment thus making the <110> direction appear with a simple visual inspection under a microscope.

2. Design Detail

The proposed pre-etched pattern consists of circular openings patterned on four concentric arcs. The patterns are arranges such that the line joining the diameters of all the four radial circles when extended would pass through the center of the wafer. Schematic diagram and the optical image of the patterns are shown in Fig. 2(a) and (b). The number of circular patterns on each arc depends on the inaccuracy of the wafer flat. In our analysis, we have patterned 49 circles of diameter 100 μm each on each arc at an angular period of 0.17^{o}. It is to be noted here, that the diameter of the circular pattern as well as the angular pitch can be further reduced for better visualization of notch-to-notch alignment which is explained in the subsequent sections. The dimensions of the proposed patterns are tabulated in Table 1.

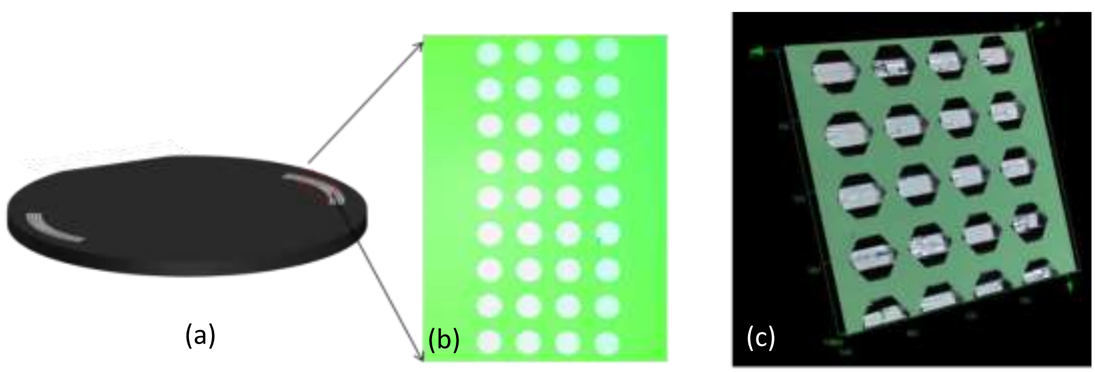


Fig. 2: The proposed pre-etched patterns for determining <110> direction on {110} surface: (a) Schematic diagram showing the arrangement of patterns at the periphery of the wafer, (b) Optical image of the patterns, (c) 3D optical image showing the etched profile and the formation of hexagonal groove.

3. Experimental Details

Cz-grown silicon wafers (p-type, boron doped) with {110} surface are used in this work. The wafer used is 4 inches in diameter with a resistivity of 1-10 ohm-cm. A 0.5 µm thick oxide layer grown using thermal oxidation is used as the masking layer in anisotropic etchant. The wafer is spin coated with a positive photoresist, followed by soft bake for 30 minutes at 90^{o} C. The proposed pattern, as shown in Fig. 2(b), is then transferred to the wafer surface using UV exposure. In order to align the mask pattern along <110> crystallographic direction wafer flat is used as the reference <110> direction. Thereafter, the photoresist is developed in developer and rinsed in DI water. Finally, hard bake is done at 120^o C for 30 minutes. Now, the oxide etching is carried out in buffered hydrofluoric acid (BHF) to expose the silicon at the circular patterns. Thereafter, photoresist is removed in acetone and the wafer is cleaned in piranha bath followed by thorough rinsed in DI water. Now anisotropic etching is carried out in 25 wt% TMAH at 70^o C. The oxide layer acts as the mask in TMAH solution. The circular pattern then takes the shape of hexagonal geometry with two slanted {111} planes and four vertical {111} sidewalls as shown in Fig. 1(b). Near the precise <110> direction, the notch of all the four radial hexagons are aligned in straight line. The precise alignment of hexagons' notches provides accurate <110> direction which is used as reference for the perfect alignment of mask pattern along crystallographic directions The accuracy of the proposed method is determined by fabricating long channels on Si{110} wafer which is discussed in next section.

Table 1: The dimensions of the proposed pre-etched pattern.

Quantity	Value
Wafer Orientation	Si{110}
Number of Circular Pattern	49 on each arc
Number of Arc	4
Diameter of circular pattern	100 μm
Angular Period	0.17^o

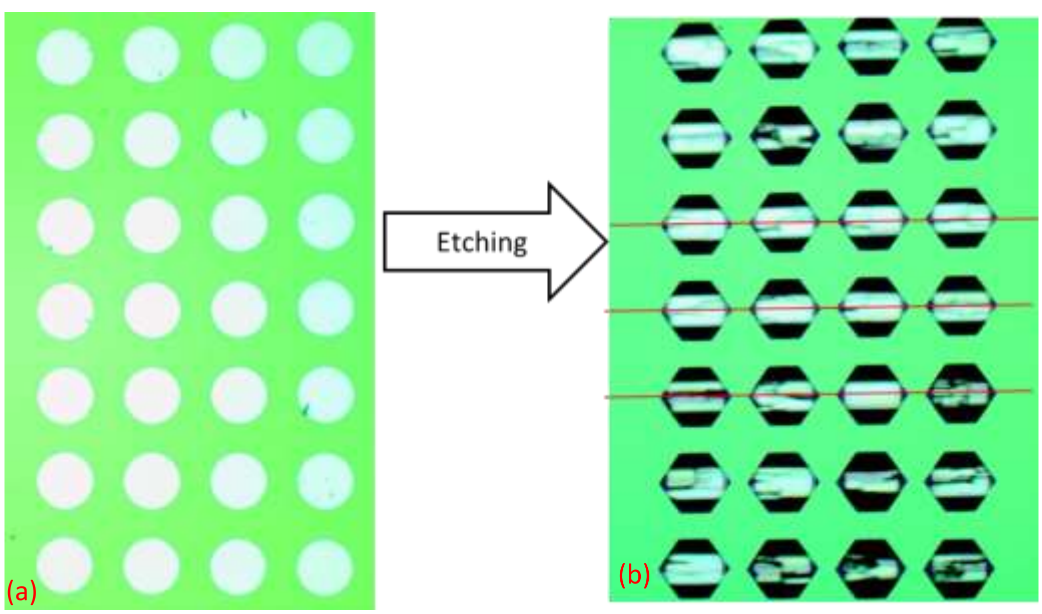


Fig. 3: The proposed pre-etched patterns: Optical images of (a) the patterned geometry and (b) the pattern after etching in 25 wt% TMAH for 45 minutes. Near the precise <110> direction (center), the notch of all the four radial hexagons are aligned in a straight line whereas at directions away from <110> (top and bottom), the notches are misaligned and does not lie on a straight line.

4. Results and Discussion

Figures 3 and 4 present the optical images of the etched patterns. As described previously, the circular openings take the shape of hexagons. At the same time, near the precise <110> direction, the notch of all the four radial hexagons lie on a straight line. At directions away from <110> direction, these notches do not lie on straight line and the misalignment can be clearly seen. It is also to be noticed that the misalignment changes its direction across the precise <110> direction. As a result, these etched patterns also reduce the domain over which a closer visual inspection is required in order to determine the precise <110> direction. Unlike the available methodologies, the proposed technique has the capability of identifying the <110> direction by a simple visual inspection using an optical microscope. It is repeated here that the distance between the circles can be further reduced in order to obtain notches even closer to each other thus enhancing the visualization of alignment of notches.

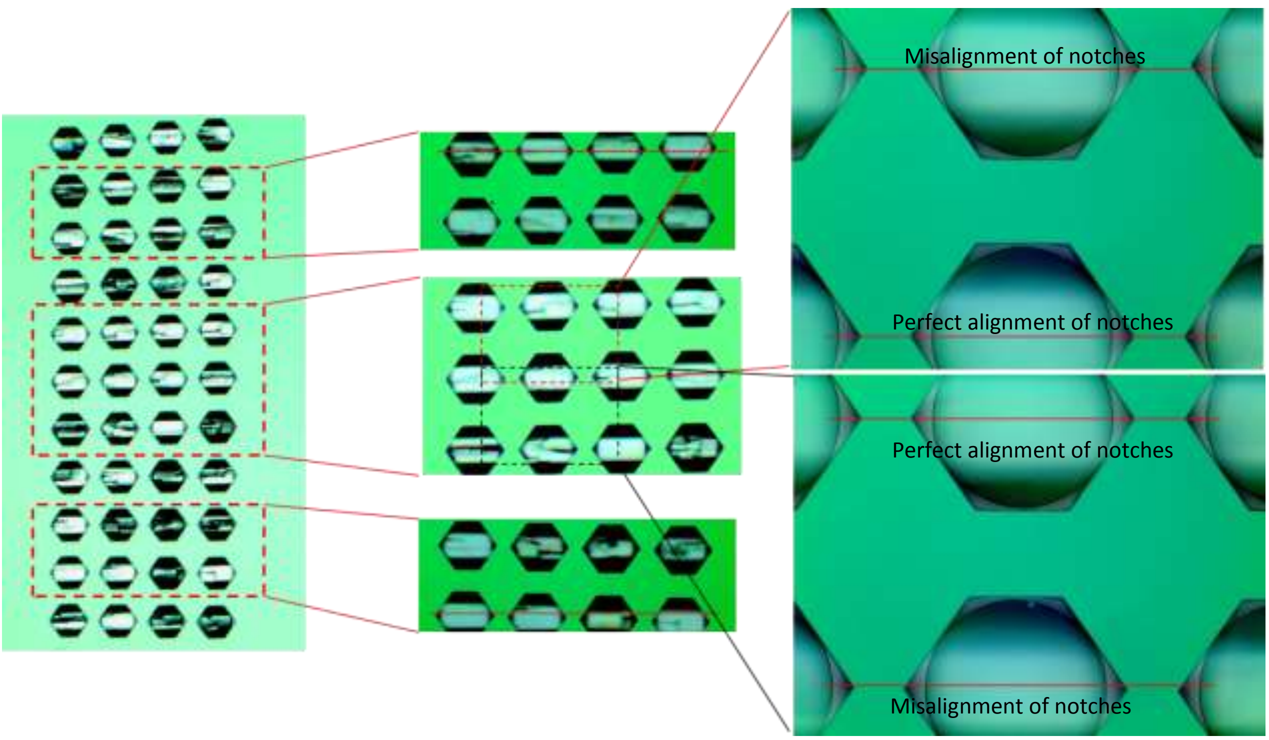


Fig. 4: Etching of the pre-etched patterns takes the form of hexagonal groove in Si{110} wafer. At the precise <110> direction, the notches of the four radial hexagons align to each other while at directions away from the precise <110>, they misalign from each other. This self-aligning behavior makes the <110> direction appears obvious and distinct.

In order to test the accuracy of the proposed method, we use the <110> direction (obtained from the proposed method) as the reference for aligning the mask edges along crystallographic directions on {110} wafer surface. We have fabricated two rectangular channels with edges along the <110> and <112> directions.

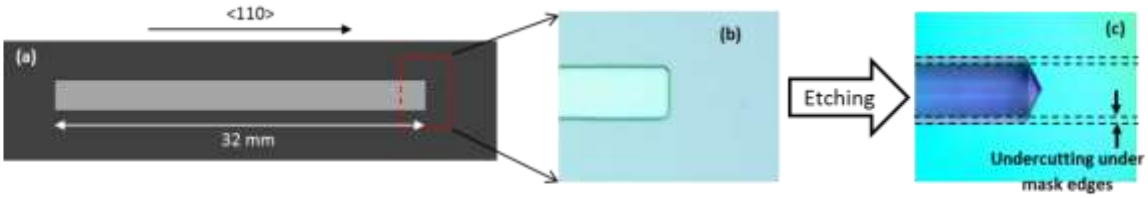


Fig. 5: A 32 mm long channel fabricated along the <110> direction: (a) Schematic diagram, (b) Optical image of the patterned channel after oxide etching, (c) Etched profile of the channel. Pre-etched patterns are used as reference for the precise alignment of the mask edges along <110> direction. Due to finite etch rate of {111} plane, undercutting occurs which is measured to be uniform along the channel length.

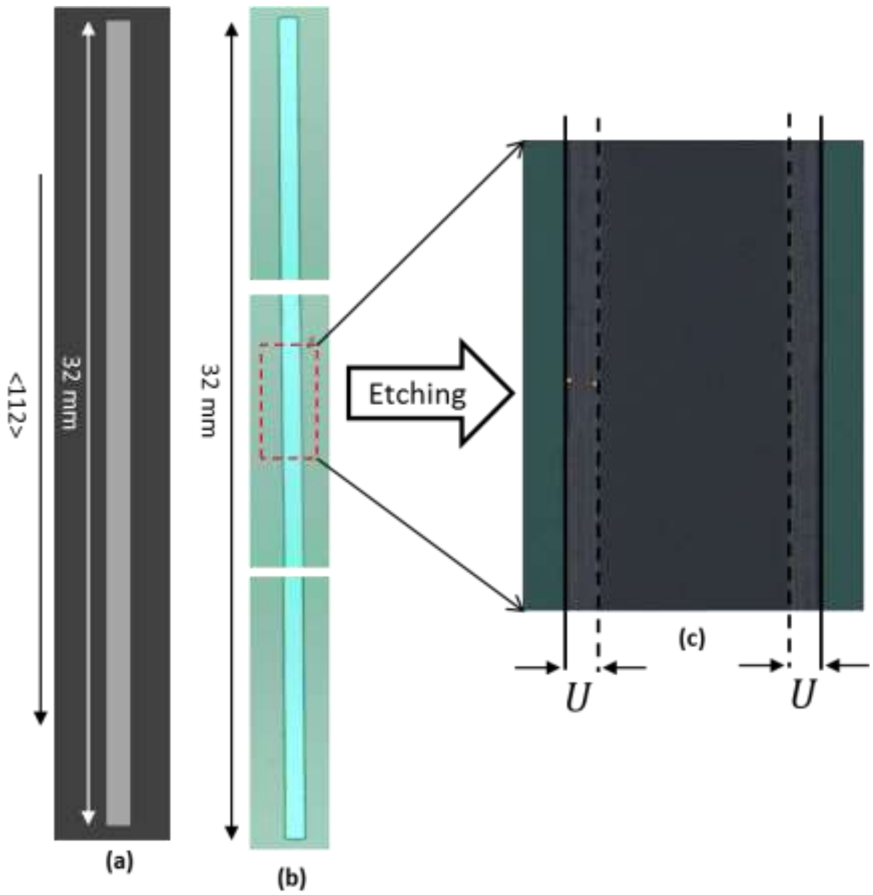


Fig. 6: A 32 mm long channel fabricated along the <112> direction using the <110> direction obtained from the proposed method as the reference: (a) Schematic diagram of the channel with longer edge aligned along the <112> direction, (b) Optical image of the patterned channel after oxide etching, (c) Zoomed image of the etched channels. It can be noticed that the undercutting (*U*) takes place due to finite etch rate of {111} plane.

The mask containing these rectangular channels is aligned in such a way that the obtained <110> direction is now used as the reference direction instead of the wafer flat as in the earlier case. Similar steps of photolithography, development and subsequent oxide etching is done. The channels are then etched in 25 wt% TMAH to obtain grooves bounded by the {111} planes.

Due to the finite etch rate of {111} planes, undercutting (U) occurs at the mask edges of the channel. This undercutting is measured at different locations along the longer edges of the channels. The mean value of these undercutting lengths measured perpendicular to the channel is found to be 5.444 μm and standard deviation of 0.633 μm for the channel oriented along the <110> direction (Figure 5) and mean undercutting value of 4.189 μm and standard deviation of 0.729 μm for the channel oriented along the <112> direction (Figure 6). We see that the variation in undercutting is within sub-micron range. Such level of uniform undercutting ensures that the crystallographic direction was accurately identified. Thus, the proposed method to determine the <110> direction on Si{110} wafer is accurate and can be effectively used to fabricate microstructures with high dimensional accuracy.

5. Conclusions

We have presented a novel self-aligning and measurement free technique using pre-etched patterns to precisely determine the <110> direction on Si{110} wafer surface. The proposed technique makes the <110> direction appears obvious and can be identified with a simple visual inspection using a microscope. This technique overcomes the challenges associated with the existing technologies where small undercut lengths needs to be measured in order to determine the direction with high precision. We have also presented the accuracy of this method by fabricating two 32 mm long rectangular channels aligned along the <110> and <112> directions, using the <110> direction obtained from the proposed method as the reference direction. The measurement of the undercutting lengths at different places along the longer edges of the channels revealed a submicron variation. This uniform undercutting ensures that the proposed technique to determine the <110> direction is accurate.

Acknowledgements

This work was supported by research grant from the Council of Scientific and Industrial Research (CSIR, Ref: 03(1320)/14/EMR-II), New Delhi, India.

References

[1] Seidel H, Csepregi L, Heuberger A, Baumgartel H (1990) Anisotropic etching of crystalline silicon in alkaline solutions I: Orientation dependence and behavior of passivation layers. J Electrochem Soc 137(11):3612-3626.

[2] Pal P, Ashok A, Haldar S, Xing Y, Sato K (2015) Anisotropic etching in low concentration KOH: Effects of surfactant concentration. Micro Nano Letters 10:224-228.

[3] Powell O, Harrison HB (2001) Anisotropic etching of {100} and {110} planes in (100) silicon. J Micromech Microeng 11:217-220.

[4] Tanaka H, Yamashita S, Abe Y, Shikida M, Sato K (2004) Fast etching of silicon with a smooth surface in high temperature ranges near the boiling point of KOH solution. Sens Actuators A 114:516-520.

[5] Baryeka I, Zubel I (1995) Silicon anisotropic etching in KOH-isopropanol etchant. Sens Actuators A 48:229-238.

[6] Backlund Y, Rosengren L (1992) New shapes in (100) Si using KOH and EDP etches. J Micromech Microeng 27:5-9.

[7] Dutta S, Imran Md, Kumar P, Pal R, Datta P, Chatterjee R (2011) Comparison of etch characteristics of KOH, TMAH and EDP for bulk micromachining of silicon (110). Microsyst Technol 17:1621-1628.

[8] Schnakenberg U, Benecke W, Lochel B (1990) NH_4OH-based etchant for silicon micromachining. Sens Actuators A 23:1031-1035.

[9] Tabata O, Asahi R, Funabashi H, Shimaoka K, Sugiyama S (1992) Anisotropic etching of silicon in TMAH solutions. Sens Actuators A 34:51-57.

[10] Gosalvez MA, Pal P, Tang B, Sato K (2010) Atomistic mechanism for the macroscopic effects induced by small additions of surfactants to alkaline etching solutions. Sens Actuators A 157:91-95.

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

[12] Zhang H, Xing Y, Gosalvez MA, Pal P, and Sato K (2015) Removal probability function for Kinetic Monte Carlo simulations of anisotropic etching of silicon in alkaline etchants containing additives. Sens Actuators A 233:451-459.

[13] Tang B, Yao MQ, Tan G, Pal P, Sato K, Su W (2014) Smoothness control of wet etched Si{100} surfaces in TMAH+Triton. Key Engineering Materials 609:536-541.

[14] Xing Y, Gosalvez MA, Sato K (2007) Step flow-based cellular automaton for the simulation of anisotropic etching of complex MEMS structures. New J Phys 9:436 (18pp).

[15] Choi WK, Thong JTL, Luo P, Tan CM, Chua TH, Bai Y (1998) Characterisation of pyramid formation arising from the TMAH etching of silicon. Sens Actuators A 71:238-243.

[16] Resnik D, Vrtacnik D, Aljancic U, Amon S (2003) Effective roughness reduction of {100} and {311} planes in anisotropic etching of {100} silicon in 5% TMAH. J Micromech Microeng 13:26-34.

[17] Pal P, Sato K (2010) Fabrication methods based on wet etching process for the realization of silicon MEMS structures with new shapes. Microsyst Technol 16:1165-1174

[18] Xu YW, Michael A, Kwok CY (2011) Formation of ultra-smooth 45◦ micromirror on (100) silicon with low concentration TMAH and surfactant: Techniques for enlarging the truly 45◦ portion. Sens Actuators A 166:164-71.

[19] Rola KP, Ptasinski K, Zakrzewski A, Zubel I (2014) Silicon 45º micromirrors fabricated by etching in alkaline solutions with organic additives. Microsyst Technol 20:221-226.

[20] Yagyu H, Yamaji T, Nishimura M, Sato K (2010) Forty-five degree micromirror fabrication using silicon anisotropic etching with surfactant-added tetramethylammonium hydroxide solution. Jpn J Appl Phys 49:096503(1-8)

[21] Tang B, Sato K (2011) Formation of silicon nano tips in surfactant-modified wet anisotropic etching. Applied Physics Express 4:56501(1-3).

[22] Holke A, Henderson HT (1999) Ultra-deep anisotropic etching of (110) silicon. J Micromech Microeng 9:51-57.

[23] Kendall D L (1979) Vertical etching of silicon at very high aspect ratios. Annu. Rev. Mater. Sci. 9:373-403.

[24] Pal P, Sato K (2009) Complex three dimensional structures in Si{100} using wet bulk micromachining. J Micromech Microeng 19:105008 (9pp).

[25] Lu H, Zhang H, Jin M, He T, Zhou G, Shui L (2016) Two-layer microstructures fabricated by one-step anisotropicwet etching of Si in KOH solution. Micromachines 7:1-7

[26] Kim HS, Kim JM, Bang YS, Song ES, Ji CH, Kim YK (2012) Fabrication of a vertical sidewall using double-sided anisotropic etching of (100) oriented silicon. J Micromech Microeng 22:095014 (11pp)

[27] Pal P, Sato K, Gosalvez M A, Tang B, Hida H, Shikida M (2011) Fabrication of novel microstructures based on orientation dependent adsorption of surfactant molecules in TMAH solution. J Micromech Microeng 21(1):015008 (11pp).

[28] Pal P, Sato K (2015) A comprehensive review on convex and concave corners in silicon bulk micromachining based on anisotropic wet chemical etching. Micro Nano Syst Lett 3:1-42.

[29] Ashok A, Pal P (2015) Silicon micromachining in 25 wt% TMAH without and with surfactant concentrations ranging from ppb to ppm. Microsyst Technol 1-8.

[30] Lee S, Park S, Cho D (1999) The surface/bulk micro- machining (sbm) process: a new method for fabricating released microelectromechanical systems in single crystal silicon. J Microelectromech Syst, 8:409-416.

[31] Pal P, Chandra S (2004) Bulk-micromachined structures inside anisotropically etched cavities. Smart Mater Struct 13:1424-1429.

[32] Pal P, Sato K (2009) Various shapes of silicon freestanding microfluidic channels and microstructures in one step lithography. J Micromech Microeng 19(5):055003 (11pp).

[33] Pal P, Singh, SS (2013) A simple and robust model to explain convex corner undercutting in wet bulk micromachining. Micro Nano Systs Lett 1:1-6.

[34] Pal P, Singh SS (2013) A new model for the etching characteristics of corners formed by Si {111} planes on Si {110} wafer surface. Eng 5:1-8.

[35] Ahn M, Heilmann RK, Schattenburg ML (2007) Fabrication of ultrahigh aspect ratio free standing gratings in Silicon on insulator wafers. J Vac Sci Technol.B 25:2593-2597.
[36] Tolmachev VA, Granitsyna LS, Vlasova EN, Volchek BZ, Nashchekin AV, Remenyuk AD and Astrova EV (2002) One-dimensional photonic crystal obtained using vertical anisotropic etching of silicon. Semiconductors 36:932-935.
[37] Zubel I, Kramkowska M (2009) Possibilities of extension of 3D shapes by bulk micromachining of different Si (h k l) substrates J Micromech Microeng 15:485-493.
[38] Lee D, Yu K, Krishnamoorthy U, Solgaard O (2009) Vertical mirror fabrication combining KOH etch and DRIE of (1 1 0) silicon. J Microelectromech Syst 18:217-227.
[39] Pal P, Gosalvez M A, Sato K, Hida H, Xing Y (2014) Anisotropic etching on Si{110}: Experiment and simulation for the formation of microstructures with convex corners. J Micromech Microeng 24:125001 (25pp).
[40] Pal P, Haldar S, Singh SS, Ashok A, Xing Y, Sato K (2014) A detailed investigation and explanation to the appearance of different undercut profiles in KOH and TMAH. J Micromech Microeng 24: 095026 (9pp).
[41] Ciarlo D R (1992) A latching accelerometer fabricated by the anisotropic etching of (110) oriented silicon wafers. J. Micromech Microeng 2:10-13.
[42] James TD, Parish G, Winchester K J and Musca CA (2006) A crystallographic alignment method in silicon for deep, long microchannel fabrication. J Micromech Microeng 16:2177-2182.
[43] Tseng FG, Chang KC (2003) Precise [100] crystal orientation determination on {110} oriented silicon wafers. J Micromech Microeng 13:47-52.
[44] Chang WH, Huang YC (2005) A new pre-etching pattern to determine (1 1 0) crystallographic orientation on both (100) and (1 1 0) silicon wafers. Microsys Technol 11:117-128
[45] Ensell G (1996) Alignment of mask patterns to crystal orientation. Sens Actuators A 53:345-348
[46] Lai JM, Chieng WH, Huang YC (1998) Precision alignment of mask etching with respect to crystal orientation. J Micromech Microeng 8:327-329
[47] Vangbo M, Baecklund Y (1996) Precise mask alignment to the crystallographic orientation of silicon wafers using wet anisotropic etching. J Micromech Microeng 6:279-284.
[48] Singh S S, Veerla S, Sharma V, Pandey A K, Pal P (2016) Precise identification of <100> directions on Si {001} wafer using a novel self-aligning pre-etched technique J Micromech Microeng 26:25012(5pp).