Jurnal Teknologi

Full Paper

SIMULATION STUDY OF CONVEX CORNER UNDERCUTTING IN KOH AND TMAH FOR A MEMS PIEZORESISTIVE ACCELEROMETER

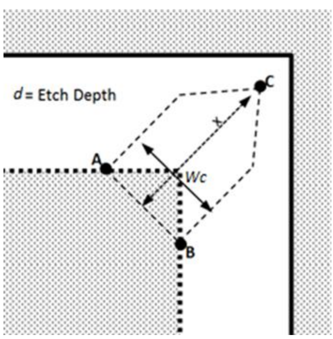
Article history
Received
6 July 2015
Received in revised form
19 April 2015
Accepted
15 May 2016

Norliana Yusof[a*], Norhayati Soin[b], Abdullah C. W. Noorakma[a]

[a]Faculty of Design Arts and Creative Technology, Universiti Sultan Zainal Abidin, Gong Badak Campus, 21300 Kuala Terengganu, Malaysia
[b]Department of Electrical Engineering, Faculty of Engineering, University of Malaya, 50603 Kuala Lumpur, Malaysia

*Corresponding author
norliana@unisza.edu.my

Graphical abstract



Abstract

Undercutting is a common problem in wet anisotropic etching. This problem in turn, influences the performance and sensitivity of MEMS devices. This paper investigates the use of corner compensation to prevent convex corner undercutting in a MEMS piezoresistive accelerometer. The Intellisuite CAD simulation software was used for designing the mask with corner compensation and for analysing wet anisotropic etching profiles in potassium hydroxide (KOH) and tetra-methyl-ammonium-hydroxide (TMAH) solutions at different concentrations and temperatures. Perfect 90 degrees corners on the proof mass was successfully etched using a corner compensation design at etching temperature of 63 °C for KOH and 67.7 °C for TMAH with 25 wt% and 10.3 wt% concentration levels, respectively. Etching in TMAH required lower concentration level, thus making the etching process safer. However, TMAH required longer time to etch perfect convex corners compared to KOH. Nevertheless, both KOH and TMAH etchants have been successfully used to etch perfect convex corners by using the designed corner compensation mask.

Keywords: Convex corner undercutting, MEMS piezoresistive accelerometer, Intellisuite CAD, KOH, TMAH

Abstrak

Keadaan potong bawah merupakan satu masalah yang biasa dalam punaran anisotropik basah. Masalah ini selanjutnya mempengaruhi prestasi dan sensitiviti peranti MEMS. Kertas kerja ini mengkaji penggunaan pampasan penjuru untuk mengelak keadaan potong bawah penjuru cembung pada meter pecut piezorintang MEMS. Perisian simulasi *Intellisuite CAD* digunakan untuk mereka bentuk topeng dengan pampasan penjuru dan juga digunakan bagi menganalisis profil punaran anisotropik basah dalam larutan kalium hidroksida (KOH) dan tetra-metil-amonium-hidroksida (TMAH) pada kepekatan dan suhu yang berbeza. Penjuru sudut 90 darjah yang sempurna berjaya dipunar pada *proof mass* dengan menggunakan reka bentuk pampasan penjuru pada suhu punaran 63 °C bagi KOH dan 67.7 °C bagi TMAH dengan tahap kepekatan KOH pada 25 wt% dan TMAH pada 10.3 wt%. Punaran dalam TMAH memerlukan kadar kepekatan yang lebih rendah, sekaligus menjadi proses punaran lebih selamat. Namun begitu, TMAH mengambil masa yang lebih lama untuk menghasilkan punaran penjuru cembung yang sempurna berbanding KOH. Walau bagaimanapun, kedua-dua larutan KOH dan TMAH berjaya digunakan untuk menghasilkan punaran penjuru cembung sempurna dengan menggunakan topeng pampasan penjuru yang direka.

Kata kunci: Keadaan potong bawah penjuru cembung, sensor MEMS Piezoresistor, Intellisuite CAD, KOH, TMAH

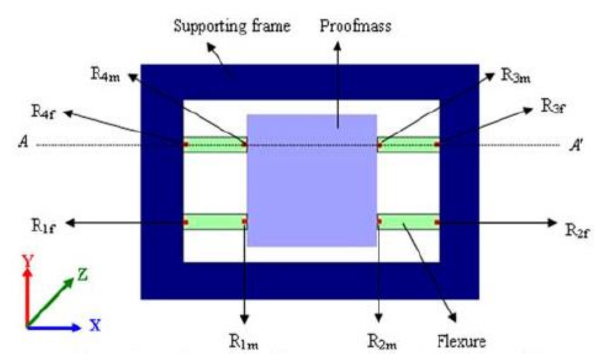
1.0 INTRODUCTION

The Micro-electro-mechanical systems (MEMS) accelerometer is an important device used in various fields, such as the automobile industry, biomedical instruments, robotic systems, navigation, electronic devices and aerospace application. Piezoresistive, capacitive and piezoelectric acceleration sensing principles are commonly used to convert mechanical motion into an electrical signal; with each sensing principle having its advantages and limitations. This paper studies a MEMS piezoresistive accelerometer for its simple structure, simple fabrication process and read out circuit compared to other accelerometers. Additionally, they are less susceptible to parasitic capacitance and electromagnetic interference as well as have low loading effects [1]. Moreover, accelerometers developed by using other techniques (capacitive, piezoelectric and tunneling) require further attention due to complex fabrication technologies and other related issues, such as optimization of on-chip interface circuitry, packaging and noise reduction techniques [2]. High precision bulk micromachining by wet chemical etching has been used to shape intricate three-dimensional structures, such as proof masses, cantilevers, diaphragms, trenches and nozzles on silicon substrates [3]. Although dry etching techniques (RIE and DRIE) are employed for high aspect ratio in silicon micromachining, wet chemical etching still dominates over dry etching due to its low process cost, simple etch setup, higher etch rate, better surface smoothness, high degree of anisotropy and lower environmental pollution [4]. Previous literature has reported that etching parameters, such as temperature and concentration of the etchants are important factors that can affect the corner undercutting of MEMS structures [5]. Potassium hydroxide (KOH) and tetra-methyl-ammonium-hydroxide (TMAH) are the most widely used etchants in anisotropy wet etching. Both have their own advantages and disadvantages. KOH provides a very high R {100}/R {111} ratio, where R is the etch rate of the corresponding planes, but it shows very poor selectivity between Si and SiO_2. Moreover, it is not compatible with the complementary metal–oxide semiconductor (CMOS) process. In contrast, TMAH is CMOS compatible and provides very good selectivity between Si and SiO_2, but with etch rate ratio of R {100}/R {111} that is lower than KOH [6]. However, one of the critical problems that occur during wet anisotropic etching of MEMS structures is the deformation of the edges due to undercutting [7], [8]. The undercutting at convex corners occurs due to the emergence of high indices crystallographic planes. These planes have high etch rates compared to {100} planes [6]. Various techniques have been proposed for etching perfect convex corners, such as corner compensation structures, local oxidation of silicon (LOCOS) processes [9], lithography on anisotropic etched patterns [6], combination of masked and maskless anisotropic etching [10], shifting of the proof mass' vertical edges towards its center [2], and adding surfactants to the etching solution [11]. Among these techniques, the corner compensation method is the most widely used technique for the fabrication of sharp convex corners [6]. This paper investigates the undercutting phenomenon at convex corners of thin flexures of piezoresistive accelerometer in KOH and TMAH solutions, which involves the design of corner compensation masks.

1.1 MEMS Piezoresistive Accelerometer

Piezoresistive accelerometer measures the electrical resistance of a material when mechanical stress is applied. According to the topological configurations of the sensing elements, the reported piezoresistive accelerometers can be classified into single clamped beams, double clamped beams, axially loaded beams and some special sensing structures with several combinations of the configurations [12].

In this work, the accelerometer was designed based on double clamped beams. The designed accelerometer consisted of a proof mass suspended by four thin flexures that were fixed to an outer supporting frame, as shown in Figure 1a [1]. The frame was fixed to the system, whose acceleration was to be measured. As the system accelerated, the frame moved with it. The proof mass, due to its inertia, will try to remain in its earlier position. In the process, it will get deflected up and/or down, depending on the direction of the motion of the system. As a result, stress will develope at the frame and at the end of each flexure.



(Rf's and Rm's denote frame side and mass side resistors respectively)

Figure 1a Structure of a piezoresistive accelerometer [1]

To measure the stress, two piezoresistors were implanted at the maximum stress points on each flexure; one in the frame end and another in the proof mass' end. Overall, eight piezoresistors were connected in a Wheatstone Bridge configuration for acceleration measurement. In a piezoresistive sensing mechanism, the change in the resistance value of the diffused resistors is proportional to the developed stress, which is proportional to the displacement of the proof mass. In this study, the fixed–fixed quad beam bridge-type structure was considered. The deflection

(ΔZ) of the proof mass, for Z-axis acceleration is given by Equation 1 [13]:

$$\Delta Z = \frac{M a_z l_b{}^3}{4Ewh} = \frac{M a_z}{K_z} \qquad (1)$$

where, M is the mass of the proof mass, a_z is the acceleration along z-axis, and E is the Young's modulus for silicon. Meanwhile, l_b, w and h are the length, width and thickness of the flexures, respectively, and K_z is the spring constant of the structure along z-axis.

The change in the resistance value of each piezoresistor has to be determined to measure the applied acceleration in the desired direction. The change in current through each piezoresistor will be obtained and thus, the new resistance value of each piezoresistor will be determined for a particular acceleration. Subsequently, changes in resistance (ΔR) and the ratio, $\Delta R/R$ can be calculated. Prime-axis sensitivity (S) of the device is defined as the change of output voltage (ΔV) per relative change of applied acceleration (ΔA), given by Equation 2 [13]:

$$S = \left(\frac{\Delta V}{\Delta A}\right)\left(\frac{1}{V_S}\right) = \left(\frac{\Delta R}{R}\right)\left(\frac{1}{\Delta A}\right) \qquad (2)$$

where V_s is the Wheatstone bridge supply voltage. The change in the output voltage of the Wheatstone bridge is calculated using Equation 3 [13]:

$$\Delta V = \frac{\Delta R}{R} V_S \qquad (3)$$

The problems of undercutting at the convex corners will reduce the sensitivity of the MEMS accelerometer since sensitivity is dependent on the area of the proof mass. The undercutting problem occurs because of the deformation of the square corner edges. It will reduce the area of the proof mass, hence reducing the sensitivity of the sensor. Thus, the undercutting problem is one of the crucial problems that must be solved in order to achieve a better performance.

1.2 Corner Compensation Techniques

Undercutting at convex corners occurs due to the emergence of high indices crystallographic planes [6]. With the corner compensation method, extra masks called the compensation structures are added at the convex corners. In order to obtain an accurate, short etching time and space efficient designs, various shapes of corner compensation structures have been proposed. Among them, the square compensation is a space efficient compensation, but it cannot give perfect convex corners [14]. However, the most widely used shape is the <100> oriented compensating beam as it can give perfect convex corners and has a simple design [8]. In this design, the width (W_c) of the additional mask is influenced by the etching depth (d) of the groove: W_c = 2 d, as shown in Figure 1b [15].

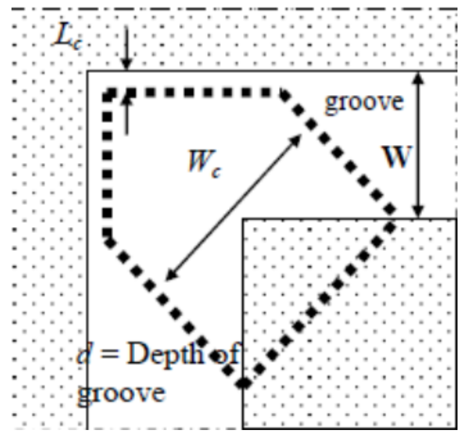


Figure 1b The <100> oriented compensating beam [15]

2.0 METHODOLOGY

The structure of the accelerometer was based on the research work by A.Ravi Sankar *et al*. [1]. The accelerometer was designed for aircraft motion sensing applications and the performance specification of this device is as proposed by A.Ravi Sankar *et al*. [1]. The masks of the accelerometer were modeled and visualized using AniSE, the Intellisuite Simulation software. The structural parameters of the accelerometer are given in Table 1. The masks used for the etching of the accelerometer are shown in Figure 2. The shape of the corner compensation masks used in this study is detailed in our previous paper [16]. The dotted lines in Figure 3 show the masks of the corner compensation design. Points A and B indicate the meeting point where undercut areas often occur. The theory states that the width depends on the etching depth: W_c = 2 d, where W_c and d are the width and the etch depth, respectively [15]. The width of this compensation mask was fixed at 246 µm since the etch depth was 123 µm. Meanwhile, the value of *x* was determined by adjusting point C via trial and error during simulations. The value of *x* in this design was determined to be 368 µm. The mask of the accelerometer with the corner compensation model was simulated using KOH and TMAH etchant solutions. A comparison of significant etching parameters was done for both etchants.

Table 1 Dimensions of accelerometer [1]

Element	Dimensions		
	Length (µm)	Width (µm)	Thickness (µm)
Proof mass	3360 (Front side) 3080 (Back side)	3500 (Front side) 3500 (Back side)	270
Flexures	1200	250	30
Piezoresistors	200	20	2
Overall Dimensions	8000	8000	1270

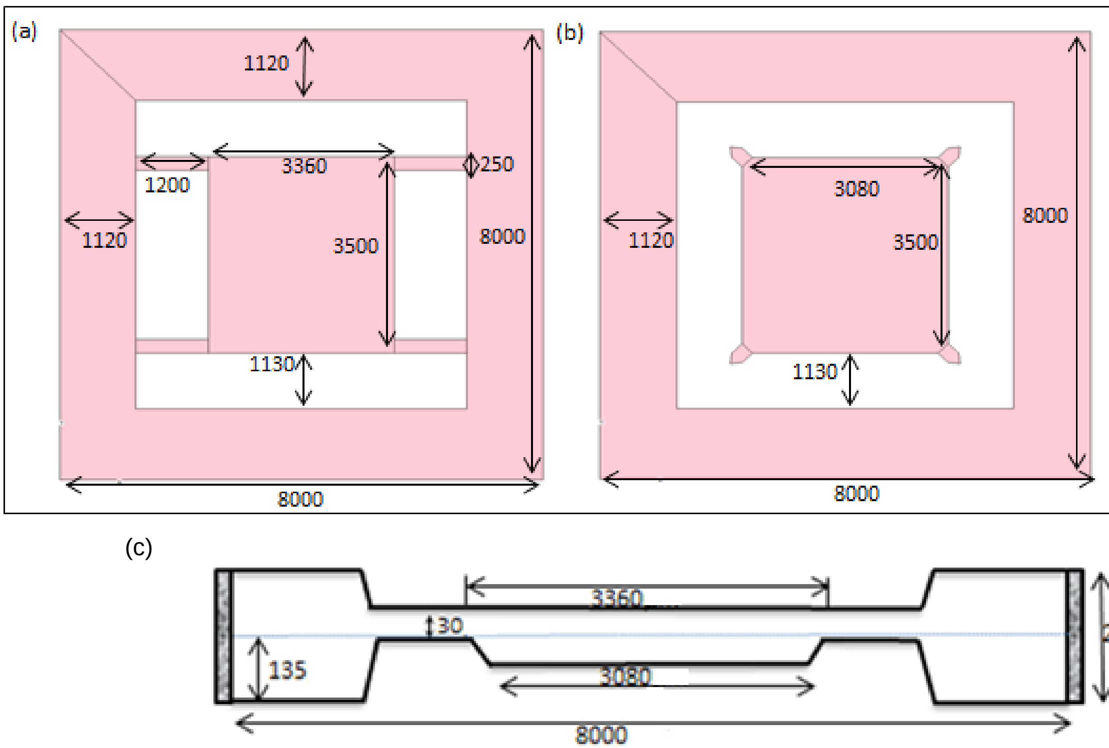


Figure 2 (a) Top mask; **(b)** Bottom mask; **(c)** cross section view of accelerometer's mask (all dimensions are in micrometers)

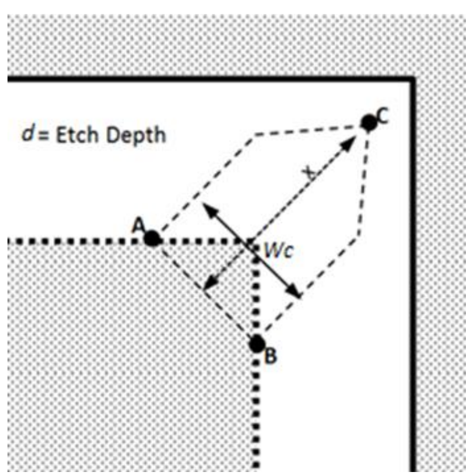


Figure 3 Corner Compensation Design

3.0 SIMULATION RESULTS AND DISCUSSIONS

3.1 Convex Corner Analysis in KOH Solution

Figure 4 shows the variation of (1 0 0) silicon etch rates for five different KOH concentrations; 15, 20, 25, 30, 35 wt%, and at different etching temperatures, ranging from 40 – 85 °C. The graph indicates that the silicon etching rate had continuously increased when the temperature was increased, irrespective of KOH solution concentration. More importantly, the graph also displays the almost identical results for KOH concentrations of 15 to 25 wt% for temperature of lower than 70°C. As indicated in Figure 5, the etching time to realize the perfect convex corners using KOH etchant was 3.8 hours. Then, this etching time was used for further analysis in order to identify the optimum temperature and concentration for the perfect convex corner, as shown in Figure 6. The lower temperature should be carried out to control the flexures' thickness [1]. In order to validate this requirement, the analysis was extended to include temperature of lower than 70 °C, as shown in Figure 6. This figure shows that the small changes in temperature had affected the undercutting structure dramatically. Nonetheless, it shows only a small effect on the structure when the concentration was increased. From Figure 6, it was observed that for temperature of lower than 63 °C, there was still a surplus on the compensation structure, while for temperature of higher than 63 °C, the undercutting problem had occurred. The simulation results have shown that under the protection of the added corner compensation mask, the perfect convex corners were entirely formed in a 25 wt% of KOH concentration at 63 °C.

3.2 Convex Corner Analysis in TMAH Solution

For TMAH etchant, the simulation of etching conditions with five different concentrations; 10, 15, 20, 25 and 30 wt% were done. The selected etching temperatures were 60, 65, 70, 75, 80 and 85 °C, respectively. Figure 7 shows the variation of etching rates of TMAH solution at different temperatures. From this figure, it can be seen that the silicon etch rates had displayed similar patterns to KOH, where the rates had increased continuously as the temperature was increased, irrespective of TMAH solution concentration. In comparison to KOH, TMAH had shown significant effects on the etching rates when the temperature and the concentration were altered. These results are in agreement with a research conducted by M . Shikida *et al*. [17]. Figure 8 shows that the etching time for producing perfect convex corners using TMAH in this simulation was 5.15 hours. Even though the etching process by TMAH had required extra etching time, one of the advantages of this additional time is that it can be used to overcome the problem of thickness non-homogeneity of the wafer [18]. Figure 9 shows the etched morphology of the convex corner structures at 5.15 hours with different temperature and TMAH concentrations. It was discovered that the perfect 90° convex corners were realized at 67.7 °C with 10.3 wt% of TMAH concentration. On the other hand, the undercutting problem began to develop when the temperature was increased with this concentration.

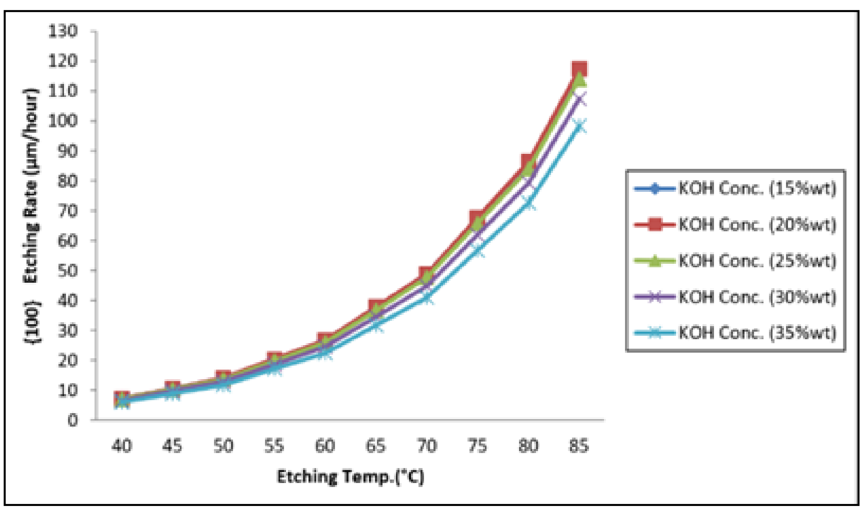


Figure 4 Variation of etching rate with KOH concentration

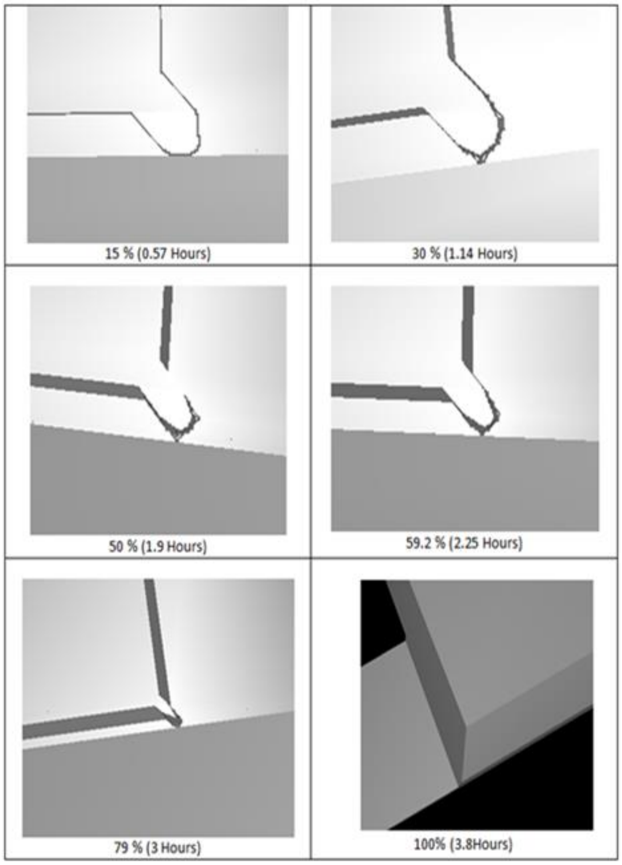


Figure 5 Percentage of etching and required etching time in KOH solution

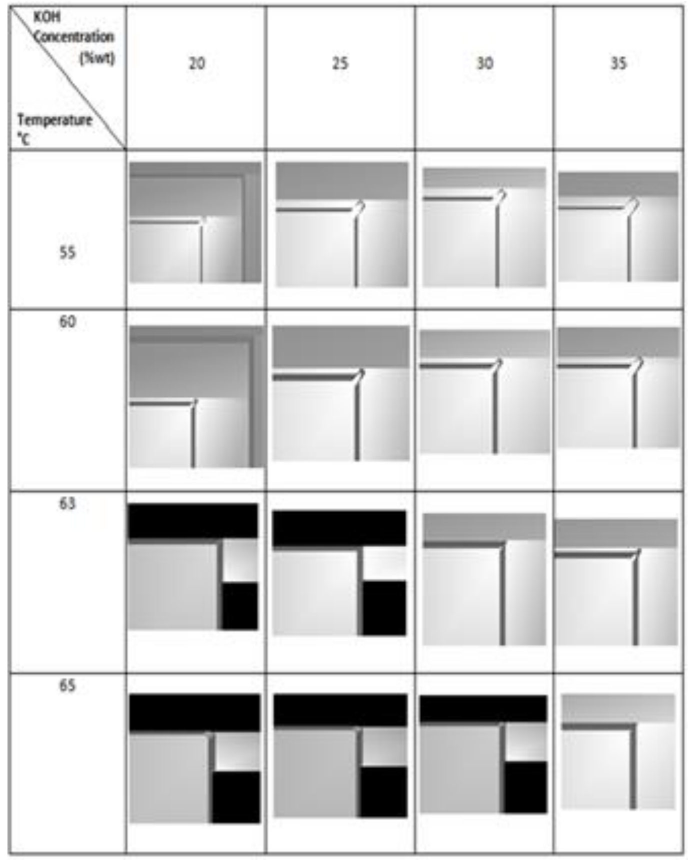


Figure 6 Etched morphology of convex corner structure at 3.8 hours, with different temperatures and KOH concentrations

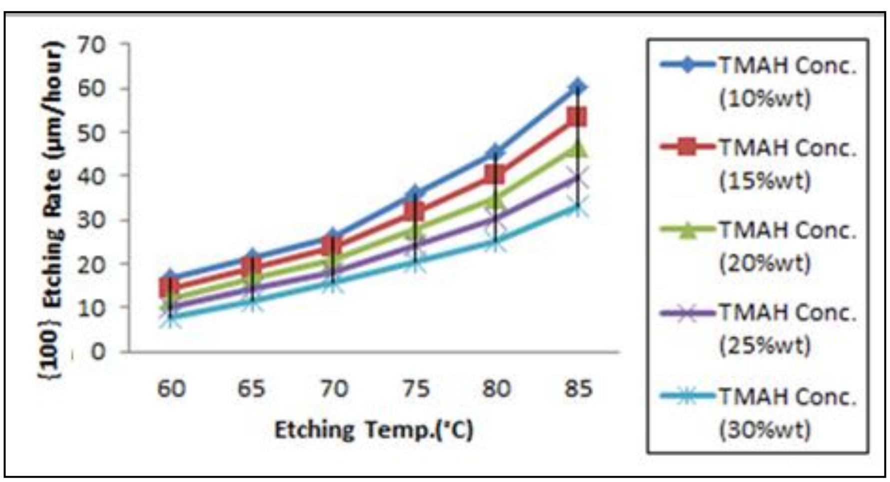


Figure 7 Variation of etching rate with TMAH concentration

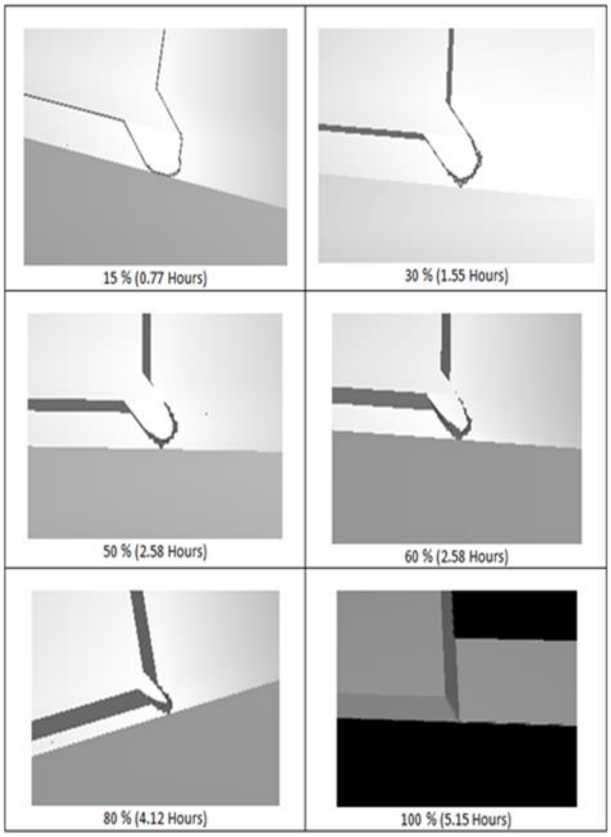


Figure 8 Percentage of etching and required etching time in TMAH solution

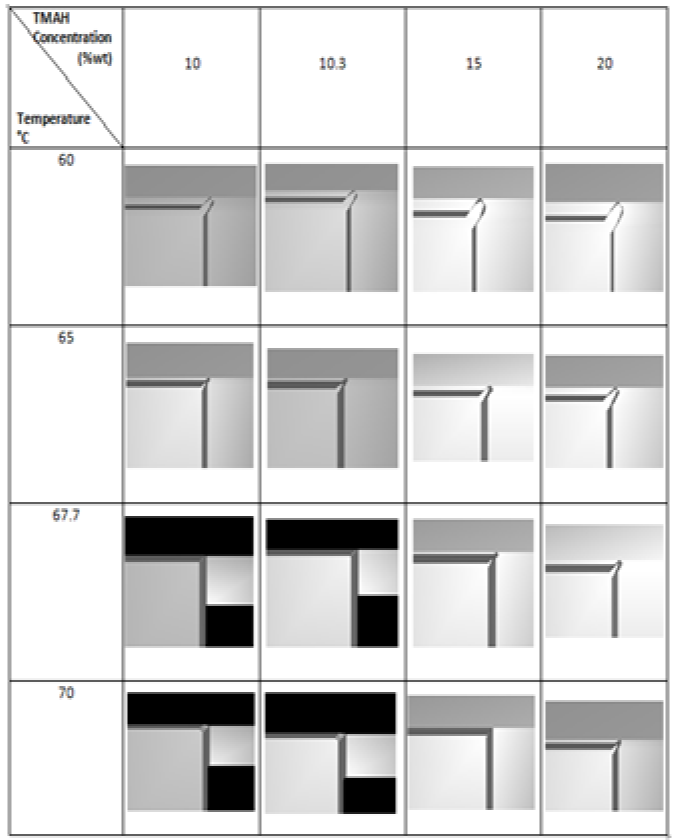


Figure 9 Etched morphology of convex structure at 5.15 hours at different temperatures and TMAH concentrations

4.0 CONCLUSION

A corner compensation mask was designed for a piezoresistive accelerometer to avoid the convex corner undercutting problem in anisotropic etching using KOH and TMAH solutions. The etching process using KOH had shown that the compensation masks had successfully protected the accelerometer's structure at etching temperature of 63 °C in 25 wt% concentration. Additionally, the 90° convex corner can be realized at 67.7 °C and in 10.3 wt% of TMAH concentration. Since KOH had exhibited higher etch rates compared to the TMAH solution, it has the advantage of shorter etching time compared to TMAH. On the other hand, TMAH required a lower concentration level, making the etching process safer. Nevertheless, both KOH and TMAH etchants have been successfully used to realize the perfect convex corners by using the designed corner compensation masks.

Acknowledgement

The authors would like to thank the Ministry of Higher Education (MOHE), Malaysia for the financial support under RAGS grant (RAGS/2013/UNISZA/SG02/1), and to the Advanced Technology Cluster, UniSZA for its support.

References

[1] A. Ravi Sankar, S. Das, and S. K. Lahiri. 2008. Cross-axis Sensitivity Reduction Of A Silicon MEMS Piezoresistive Accelerometer. *Microsystem Technology*. 15(4): 511-518.

[2] A. Ravi Sankar, J. G. Jency, J. Ashwini, and S. Das. 2012. Realisation Of Silicon Piezoresistive Accelerometer With Proof Mass-Edge-Aligned-Flexures Using Wet Anisotropic Etching. *Micro & Nano Letters*. 7: 118-121

[3] S. Dutta, M. Imran, P. Kumar, R. Pal, P. Datta, and R. Chatterjee. 2011. Comparison Of Etch Characteristics Of KOH, TMAH And EDP For Bulk Micromachining Of Silicon (110). *Microsystem Technology*. 17(10-11): 1621-1628.

[4] K. Biswas and S. Kal. 2006. Etch characteristics of KOH, TMAH And Dual Doped TMAH For Bulk Micromachining Of Silicon. *Microelectronics J*. 37(6): 519-525.

[5] Norhayati Soin and Burhanuddin Y.Majlis. 2006. Characterization of Anisotropic Etching Effects of KOH Concentration and Temperature on Etching Profiles Properties of Silicon Corrugated Diaphragm. *American Institute of Physics Conference Proceedings, 2006*. 909: 128-132.

[6] P. Pal, S. Haldar, S. S. Singh, A Ashok, X. Yan, and K. Sato. 2014. A Detailed Investigation And Explanation Of The Appearance Of Different Undercut Profiles in KOH and TMAH. *J. Micromechanics Microengineering*. 24(9): 095026

[7] X. P. Wu and W. H. Ko. 1989. Compensating Corner Undercutting In Anisotropic Etching Of (100) Silicon. *Sensors and Actuators*. 18(2): 207-215.
[8] P. Pal, K. Sato, and S. Chandra. 2007. Fabrication Techniques Of Convex Corners In A (1 0 0)-Silicon Wafer Using Bulk Micromachining: A Review. *J. Micromechanics Microengineering*. 17(10): R111-R133.
[9] Prem Pal and Sudhir Chandra. 2004. A Novel Process For Perfect Convex Corner Realization In Bulk Micromachining. *J. Micromechanis Microengineering*. 14: 1416-1420.
[10] M. M. Smiljanić, V. Jović, and Ž. Lazić. 2012. Maskless Convex Corner Compensation Technique On A (1 0 0) Silicon Substrate In A 25 %Wt TMAH Water Solution. *J. Micromechanics Microengineering*. 22(11): 115011.
[11] B. Tang, K. Sato, S. Xi, G. Xie, D. Zhang, and Y. Cheng. 2014. Process Development Of An All-Silicon Capacitive Accelerometer With A Highly Symmetrical Spring-Mass Structure Etched In TMAH+Triton-X-100. *Sensors Actuators:A Physical*. 217: 105-110.
[12] M. H. M. Khir, P. Qu, and H. Qu. 2011. A Low-Cost CMOS-MEMS Piezoresistive Accelerometer With Large Proof Mass. *Sensors*. 11(8): 7892-907.
[13] R. P. Van Kampen and R. F. Wolffenbuttel. 1998. Modeling The Mechanical Behavior Of Bulk-Micromachined Silicon Accelerometers. *Sensors and Actuators A*. 64: 137-150.
[14] R. Mukhiya, a. Bagolini, T. K. Bhattacharyya, L. Lorenzelli, and M. Zen. 2011. Experimental Study And Analysis Of Corner Compensation Structures For CMOS Compatible Bulk Micromachining Using 25%wt TMAH. *Microelectronics J*. 42(1): 127-134.
[15] N. Soin and Burhanudin Y. Majlis. 2005. KOH Etching Process Of Perfect Square MEMS Corrugated Diaphragm. *Proceeding of Device and Process Technologies for Microelectronics, MEMS, and Photonics IV*. 6037: 60371Z-60371Z-10.
[16] N. Yusof, A. C. W. Noorakma, and N. Soin. 2014. Corner Compensation Mask Design On (MEMS) Accelerometer Structure. *IEEE International Conference Semiconductor Electron*, *2014*. 248-251.
[17] M. Shikida, K. Sato, K. Tokoro, and D. Uchikawa. 1999. Comparison Of Anisotropic Etching Properties Between KOH And TMAH Solutions. *International Conference on Micro Electro Mechanical Systems*,1999. 315-320.
[18] N. Soin and B. Y. Majlis. 2006. Development Of Perfect Silicon Corrugated Diaphragm Using Anisotropic Etching. *Microelectronic Engineering*. 83: 1438-1441.