Proceedings of 10th International Conference on Precision, Meso, Micro and Nano Engineering (COPEN 10)
December 07 – 09, 2017, Indian Institute of Technology Madras, Chennai – 600 036 INDIA

On Dimensional Accuracy in Silicon Microchannels Fabricated using Micro-USM

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Abstract

Aspect ratio (width: height) of any microchannel geometry plays a vital role in the measure of performance of a heat sink. Substrate material is another key factor which contributes to the thermal performance of a heat sink. Silicon wafer is widely used as a substrate for microchannel heat sink in microelectronic device applications. Common etching-based Si-microchannel fabrication techniques are orientation dependent; it is difficult to control etching to achieve the target aspect ratio. In the present study, microchannels were fabricated on silicon wafer with the targeted aspect ratio (W: H =) 600 μm : 300 μm using micro-USM. Experiments were performed varying different process parameters to achieve the dimensional control; outputs were analyzed using Response Surface Methodology (RSM) to optimize the process parameters. Images of the fabricated microchannels from stereo microscope were processed to verify the results. Results confirm that better dimensional accuracy could be achieved while following the optimized machining strategy.

Keywords: Micromachining, aspect ratio, abrasives, brittle fracture, optimization.

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1. INTRODUCTION

Investigation of fluid flow and heat transfer through microchannels have been studied by several researchers for different fields of application such as biotechnology, lab-on-chips, micro heat exchangers, micro reactors, electronic systems, micro-electromechanical systems (MEMS), micro-fluidic systems, etc. However, the main concern is the heat transfer enhancement. With increase in miniaturization, packing of components becomes denser which results in higher heat fluxes; this necessitates development of microchannel heat sinks. The first microchannel heat sink was fabricated by Tuckerman and Pease [1] with a dimension of width 50 μm and depth 300 μm by etching technique to dissipate a large amount of heat flux (~790 W/cm2). Later, Peiyi and Little [2] fabricated microchannels of varied dimensions by photolithographic technique for measuring the friction factors of the flow gases used in Joule-Thomson refrigerators. Numerical and experimental investigations were also performed on different aspect ratios of microchannels to study the performance of the heat sink [3, 4]. Most of the studies reveal that the performance of the heat sink depends on geometric parameters i.e., mainly on the aspect ratio of the microchannel. Investigations on different geometries such as Rectangular, Triangular and Trapezoidal microchannels showed that rectangular microchannels provides better heat transfer compared to the other geometries [5, 6].

Silicon is most widely used material for microelectronic devices due to its good physical and mechanical properties. The photolithographic and etching techniques are extensively used for fabrication of silicon microchannels. Attempts have been made to fabricate deep and smooth walled silicon microchannels by controlling the temperature, etch composition and masking orientation [7]. In the early 1990's, Sun et al., [8] came up with a new technology called micro-ultrasonic machining, for machining three dimensional microstructures with high aspect ratio in hard and brittle materials like silicon, glass, quartz, ceramics, etc. It was reported that in this technique, size and concentration of abrasive particles have great influence on the machined profile [9]. Further, it was found that the quality of machining depends on several factors such as work material properties, tool attribute and process settings [10].

In the present work, trials were carried out to fabricate the targeted aspect ratio microchannels by varying different process parameters such as abrasive concentration, abrasive size and feed rate. Response Surface Methodology optimization technique was used to analyze the results and optimize the process parameters.

2. EXPERIMENTAL

2.1 Design of Experiments

Response Surface Methodology (RSM) is an interaction of mathematical and statistical techniques useful for modeling and analyzing the model with an objective of optimizing the response variables [11]. In general a second order model is used to explain the behavior of the model; the model output (Y) is given by,

$$Y = \beta_0 + \sum_{i=1}^{k} \beta_i x_i + \sum_{i=1}^{k} \beta_{ii} x_i^2 + \Sigma\Sigma_{i<j} \beta_{ij} x_i x_j + \varepsilon \qquad (1)$$

where, x_i , x_j are regressors.

The coefficients of the model (β_0 , β_i , β_{ii} , β_{ij}) were estimated by analyzing the experimental results using 'Design Expert 10.0' software. Face centered Central Composite Design (CCD) technique with α = 1 was used to design the experiments and a set of twenty trials was conducted. The most influencing factors/ parameters abrasive grit size (A), abrasive concentration (B) and feed rate (C) [9] were selected at three levels each as shown in Table 1; response parameters being width (μm) and depth (μm).

Table 1: Levels of process parameters with coded values

CCD coded values	A: Abrasive Size (#)	B: Abrasive Conc. (%)	C: Feed Rate (mm/min)
Low (-1)	1000	15	10
Medium (0)	1400	20	15
High (1)	1800	25	20

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2.2 Fabrication of Si microchannels

Micro-ultrasonic machining (micro-USM) as shown in Fig.1 was used to fabricate the microchannels on silicon wafer, the most widely used material in electronic industry. Owing to the machine and material thickness constraints, the microchannel aspect ratio was targeted to W × H : 600 µm × 300 µm with a length of 10 mm. Tungsten carbide (WC) tools with diameter of 600 µm used to machine the microchannels with SiC abrasives in water slurry at 20 kHz; these parameters were maintained constant throughout. As per the design, twenty experiments were conducted on the P - type (100) silicon wafer by varying the selected process parameters. After completion of each experiment, the microchannels were cleaned in an ultrasonic cleaner and were examined under a stereo microscope to measure the width and depth (Figs. 2(a & b)). The measured and predicted values of width and depth are shown in the Table 2.

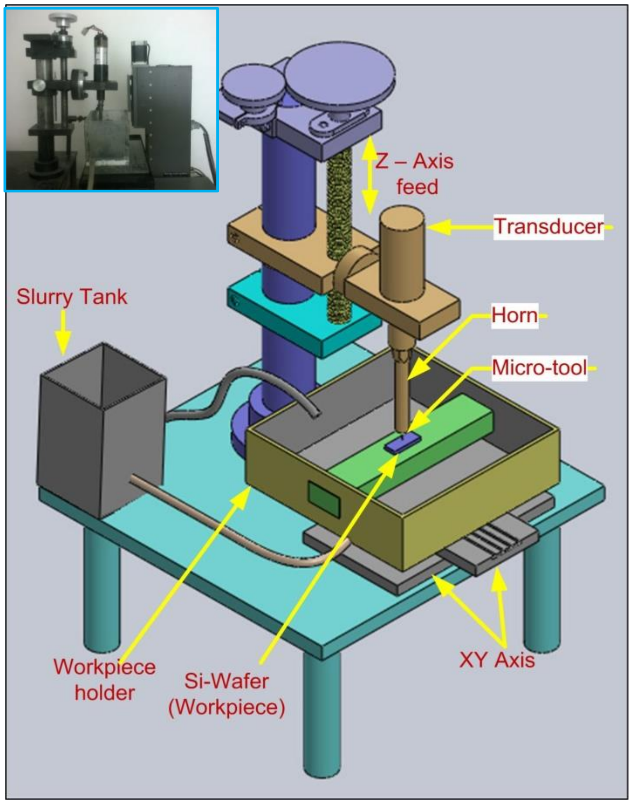

Fig. 1. Schematic of micro ultrasonic machine; *Inset*: actual photograph of the setup.

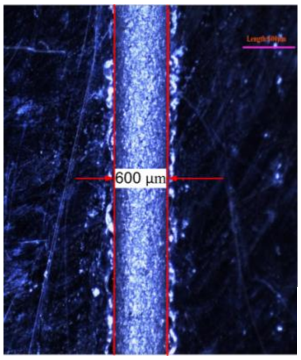

Fig. 2(a) Top view of microchannel showing the Width

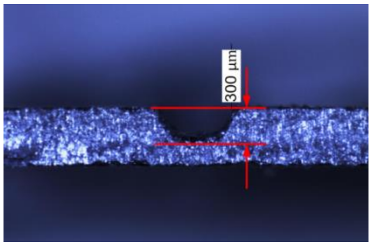

Fig. 2(b) Front view of microchannel showing the Depth

3. RESULTS AND DISCUSSION

3.1 Analysis of Results

Analysis of variance (ANOVA) was conducted at 95% confidence interval and the quadratic model was found significant. The models in the coded values are:

Table 2: Trial results according to CCD

S. No	Coded factors*			Experimental values (µm)		Predicted values (µm)		Error (µm)	
	A	B	C	Width	Depth	Width	Depth	Width	Depth
1	-1	-1	-1	634.28	297.23	633.09	297.45	1.19	-0.22
2	1	-1	-1	642.88	286.87	642.98	286.75	-0.10	0.12
3	-1	1	-1	617.31	287.94	617.63	287.88	-0.32	0.06
4	1	1	-1	635.21	290.13	634.03	289.42	1.18	0.71
5	-1	-1	1	637.1	291.22	638.33	291.04	-1.23	0.18
6	1	-1	1	637.1	275.39	636.83	274.56	0.27	0.83
7	-1	1	1	639.41	289.79	639.36	289.03	0.05	0.76
8	1	1	1	643.12	285.91	644.37	284.80	-1.25	1.11
9	-1	0	0	627.51	290.89	627.20	291.67	0.31	-0.78
10	1	0	0	634.54	281.43	634.64	284.20	-0.10	-2.77
11	0	-1	0	629.42	302.88	629.55	303.78	-0.13	-0.90
12	0	1	0	625.92	301.46	625.58	304.11	0.34	-2.65
13	0	0	-1	635.42	298.21	637.37	298.89	-1.95	-0.68
14	0	0	1	647.33	290.49	645.17	293.37	2.16	-2.88
15	0	0	0	631.34	300.02	631.96	300.20	-0.62	-0.18
16	0	0	0	634.85	302.66	631.96	300.20	2.89	2.46
17	0	0	0	632.87	305.42	631.96	300.20	0.91	5.22
18	0	0	0	629.88	298.22	631.96	300.20	-2.08	-1.98
19	0	0	0	630.52	302.89	631.96	300.20	-1.44	2.69
20	0	0	0	631.89	299.09	631.96	300.20	-0.07	-1.11

*A: Abrasive Size (#); B: Abrasive Conc. (%); C: Feed rate (mm/min)

$$Width\ (W) = 631.96 + 3.72{*}A - 1.98{*}B + 3.90{*}C + 1.63{*}AB - 2.85{*}AC + 4.12{*}BC - 1.04{*}A^2 - 4.40{*}B^2 + 9.31{*}C^2 \qquad (2)$$

$$Depth\ (H) = 300.20 - 3.73{*}A + 0.16{*}B - 2.76{*}C + 3.06{*}AB - 1.44{*}AC + 1.89{*}BC - 12.26{*}A^2 + 3.75{*}B^2 - 4.07{*}C^2 \qquad (3)$$

The results of ANOVA for fitted response surface model of Width and Depth are shown in Table 3 and Table 4 respectively.

Table 3: ANOVA for Width of the microchannel.

Source	Sum of squares	Degrees of freedom	Mean square value	F value	p-value
Model	810.60	9	90.07	29.25	<0.0001(S)
Linear	329.71	3	109.90	35.69	<0.0001(S)
Square	258.92	3	86.30	28.03	<0.0001(S)
Interaction	221.95	3	73.98	24.03	<0.0001(S)
Residual	30.79	10	3.08		
Lack of Fit	14.85	5	2.97	0.93	0.5301(NS)
Pure Error	15.94	5	3.19		
Total	841.39	19			

R^2 : 0.9634, Adjusted R^2 : 0.9305, Pred. R^2 : 0.7666,
S= significant, NS = Not Significant

Table 4: ANOVA for Depth of the microchannel.

Source	Sum of squares	Degrees of freedom	Mean square value	F value	p-value
Model	1172.91	9	130.32	17.67	<0.0001(S)
Linear	215.76	3	71.92	9.75	<0.0001(S)
Square	836.89	3	278.96	37.83	<0.0001(S)
Interaction	120.25	3	40.08	5.44	<0.0001(S)
Residual	73.75	10	7.38		
Lack of Fit	36.43	5	7.29	0.98	0.5102(NS)
Pure Error	37.32	5	7.46		
Total	1246.66	19			

R^2 – 0.9408, Adjusted R^2 – 0.8876, Pred. R^2 – 0.8174
S= significant, NS = Not Significant

The quadratic model as suggested by the RSM and the models are significant at 95% confidence level. The lack of fits is not significant which is desirable to fit a model in both the cases. The R^2 value near to unity gives better response fit of the model. The R^2 values for both Width and Depth analyses are near to unity represent a good fit. Adjusted R^2 and Predicted R^2 are also within the range for both the cases.

3.2 Influence of process parameters on Width

Fig. 3 (a-c) shows the combined effect of process parameters on the width. There is marginal increase in the width with increase the abrasive grit size and abrasive concentration. The targeted width (600 µm) could be achieved at the high levels of grit size and abrasive concentration (Fig. 3(a)). Higher level of grit size indicates fine abrasive particle and therefore, the damage at the edges will be less which could help achieving the target. Figs. 3(b) & (c) follow a near similar surface curve which indicates that the width is moving away from the target values while increasing the feed along with abrasive concentration and grit size. The reason attributed is that as the feed rate increases there will be reduced hammering action and more surficial action of the tool abrasive interaction. Consequently, there is more stray cutting instead of cutting depth wise.

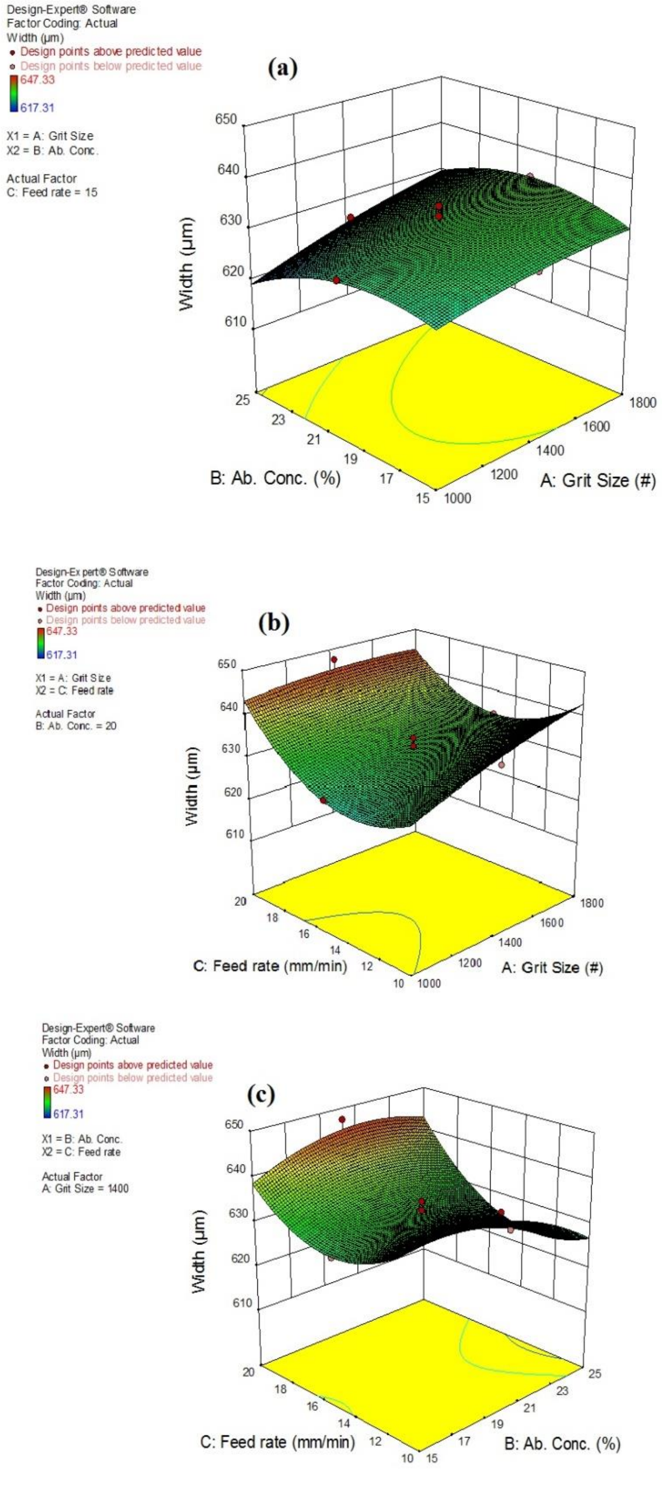

Fig. 3 (a-c) Influence of grit size, abrasive conc. and feed rate on width

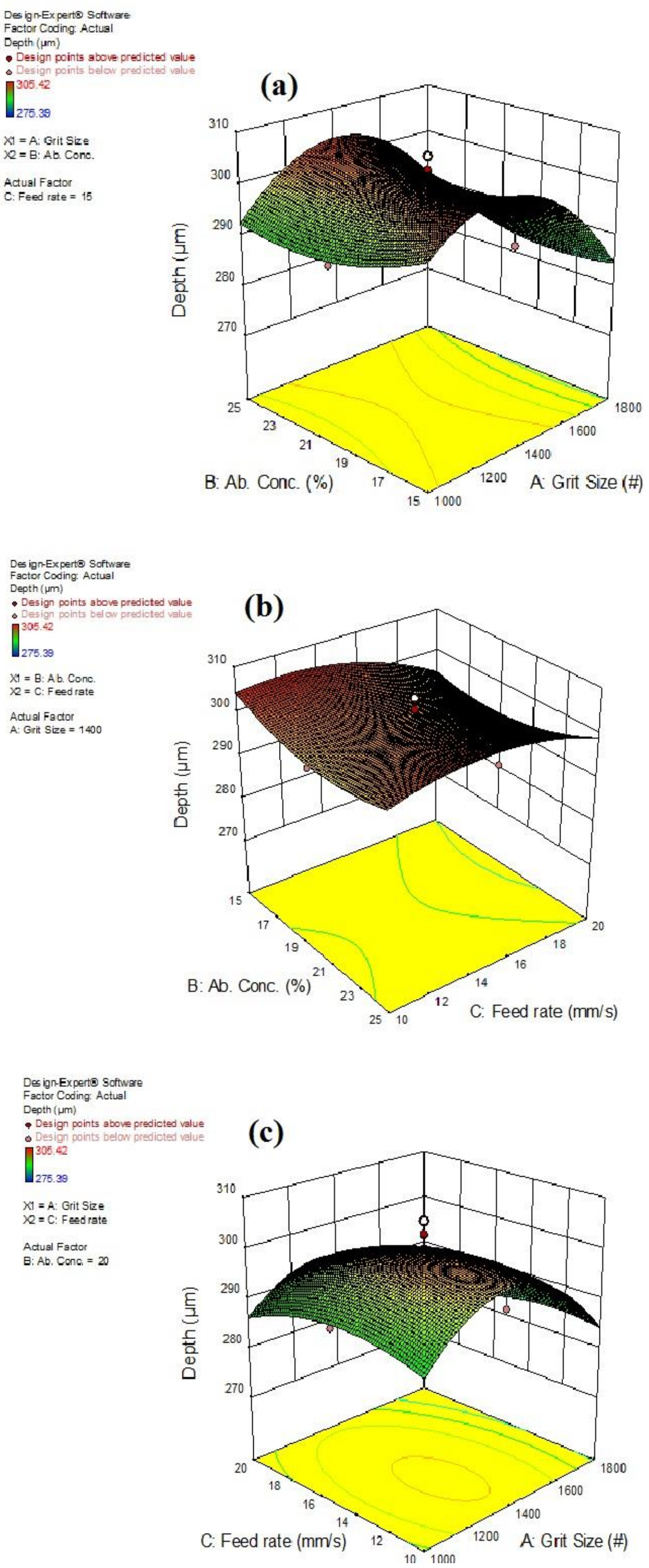

Fig. 4 (a-c). Effect of grit size, abrasive conc. and feed rate on depth

3.3 Influence of process parameters on Depth

Fig. 4 (a-c) represents the variation of response parameter (Depth) with the variation in the process parameters. The RSM predicts that a range of 275.39 µm to 305.42 µm could be achieved with the designed quadratic model. It is observed from Fig. 4(a) that response surface is near to the target value when the abrasive concentration is at the medium level and the grit size is at medium level. Similarly, from Fig. 4(b) it can be interpreted that the target value is achieved with medium level of abrasive concentration and low level of feed rate. It was observed from Fig. 4(c) that at the higher feed rate, the depth is far less than the target. The reason is that at higher feed rates, the machining time will be less and the tool moves with less machining action. Another reason may be that at higher feed rates, tool wear is high and could not achieve the target value.

3.4 Optimization

The objective of optimizing the process parameters is to achieve the targeted width and depth using a Desirability test. In the process, all the three process parameters were kept in range, i.e., between the low level and high level and the response variables were kept at their target values. The desirability with highest value which was near to unity was selected for optimality. The optimization was achieved at the desirability value of 0.989 with the optimum values of process parameters are at grit size: #1800, abrasive concentration: 25 %; feed rate: 10 mm/min.

3.5 Confirmation experiment

A set of confirmation experiments were conducted with the optimized process parameters (abrasive grit size of #1800, abrasive concentration of 25% and feed rate 10 mm/min). The width and depth obtained were 628.49 µm and 292.14 µm, respectively and were within the range, near to the target.

4. CONCLUSION

- The study reveals that the width of the channel could be fabricated near to the target with the optimized process parameters. At high feed rate, marginal widening of the channels occurs due to straying of the abrasive particles on to the edges of channel.
- The depth of the channel was achievable near to the target value; however, tool wear and less interaction time at high feed rate contributes to the reduced depth (than the target value).

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