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PARAMETRIC STUDY OF SPUTTERING MICROCHANNELS VIA FOCUSED ION BEAM (FIB)

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ABSTRACT

Focused ion beams (FIB) are used in microfabrication and have certain advantages compared to photolithography and other micromachining technologies. The main advantage is that it can be used for direct writing/patterning of the target material. FIB can create a variety of geometric features, has the ability to process without masks, and can accommodate the patterning of a variety of materials. In high aspect micromilling, the beam current, beam diameter as well as the dwell time are some of the parameters that need to be taken into account. In this research, different beam currents with respective beam diameters were used to investigate the optimum parameters that can be achieved in milling microchannels. The target material that was used in this experiment was Silicon <100>. The wafer used had 250 µm thicknesses. The results observed were the channel width, gap between the channels, and the channel depth. The main trend observed was that when the beam current increases, the depth and the channels' width also increase whereas the channels' gap decreases. Defects such as side wall tapering effect and swelling were noticed from the experiments that used the unsuitable parameters because the values of beam current are not enough to sputter the silicon surface. The best beam current use that give the nearest result to the actual pattern is around 7.0 – 8.0 pA. Extended research need to be conducted to see the effect on the surface roughness of the channels

Keywords: focused ion beam, microchannel, sputtering/milling.

INTRODUCTION

The application of focused ion beam (FIB) technology in microfabrication has become increasingly popular. FIB micromachining has been widely used in microelectronic applications such as the modification and analysis of integrated circuit and trimming of magnetic heads. The use of FIB also can be successfully extended other areas such as surgery devices, fluidic devices, and micro sensors [1].

FIB is similar to a scanning electron microscope (SEM) in many ways. The FIB technique uses a focused beam of ions to scan the surface of a specimen, analogous to the way electrons are used in the SEM. The difference is that FIB technology typically uses gallium ions (Ga+) instead of electrons as the focusing beam. The ion beam is manipulated (in terms of focus and acceleration) by an electric field. Ions have relatively high mass compared to electrons which allow them to be used for milling and deposition of material on a target surface [2].

There are four broad categories of FIB applications which are sputtering, deposition, ion implantation, and imaging. This research focuses on the sputtering/ milling application. The goal is to investigate the relationship between the parameter used for FIB sputtering such as dwell time, scanning time, beam current, and beam diameter to the depth and width of the microchannels as well as the gap between the channels of silicon sputtering.

In FIB parameters terminology, the beam diameter (nm) is the size of the column opener that will sputter the ion onto the targeted surface whereas the beam current describes the total amount of charge supplied to the substrate for a given material removed per unit time (pA). Dwell time is time for which the beam remains concentrated at a single point on the substrate material and provides ion charges at that point (µs) while scanning time is the time required for a run of experiment to be done in achieving the target geometry (µs).

It is important to know this relationship since the ability to make high-aspect-ratio microstructures is a main factor in successfully manufacturing microdevices or systems.

For milling applications, high beam currents are used to remove material from the target surface, whereas lower beam currents are for fine polishing. A lower beam current can also produce channels with a finer quality, but a greater numbers of repetitive passes is required to mill the channels, resulting in significant reduction in productivity [2].

According to Bhavsar, Aravindan, and Rao [3], overlapping between beam diameters is also an important factor in milling. This is called pixel spacing. In order to mill a smooth surface, the pixel spacing between adjacent scan lines must be small enough to allow a proper overlap. Figure-1 shows the concept of pixel spacing in FIB milling.

Research done by Stanishevsky [5] found that if the beam current is lower, the quality of the surface will increase but productivity is reduced due to the higher number of repetitive passes required to mill a given channel. In that work, the researcher used very small beam currents varying from 1.8 to 3.0 pA with a pixel spacing of 10nm and beam diameter equal or less than 12 nm. Figure-2 shows the example of the results by Stanishevsky [5]. The channels widths marked 1, 2, 5 and 6 are as small

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as 30nm and respective depths are 660, 540, 570 and 800 nm.

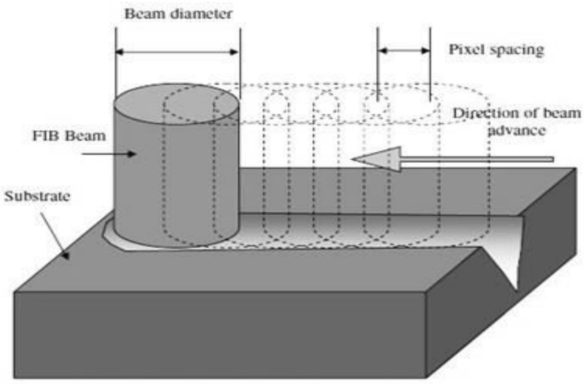

Figure-1. Schematic diagram of FIB milling that shows the beam diameter and pixel spacing [4].

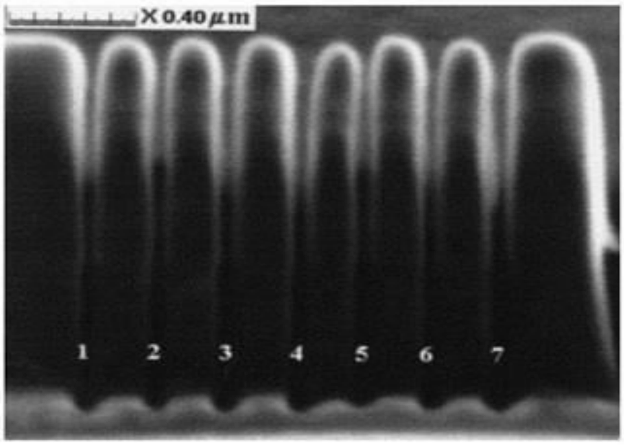

Figure-2. FIB milled channels with the widths of 30 – 40 nm and depth of 540 – 870 nm [5].

J.H. Kim *et al*. [6] also found that as the beam current is increased, the width and angle of the tapered wall becomes larger and the surface becomes rougher. This was found via experiments using different beam current conditions under the same pattern size of 3 x 3 nm², pixel spacing of 60/800 m, 30keV accelerating voltage and 50s dwell time. A smaller beam current results in better surface roughness but a longer time in milling. Figures-3 (a) and (b) show the results obtained from the experiment.

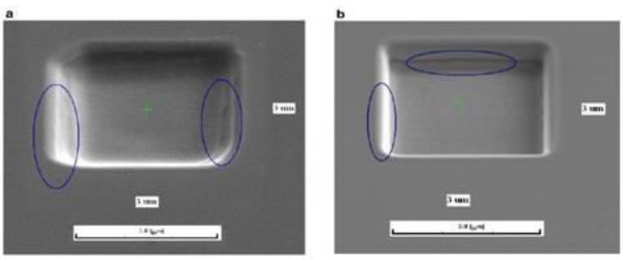

Figure-3. (a) Result of higher beam current (740.23pA) (b) Result of lower beam current (283.7pA) [6].

METHODOLOGY

The target pattern to be micro-machined using FIB consists of 5 identical microchannels where both the channel's width and gap between the channels are set at 0.3µm respectively. Figure-4 shows the pattern used throughout the experiment. The length of each channel is 10µm. The FIB used is a Helios Nanolab G3 with Ag+ ion. This machine is able to perform both FIB and SEM processes. Ranges of selected beam currents and beam diameters available were tested to identify the parameters that will provide the output that closely matches the targeted dimension.

The experiments were divided into two phases. In the first phase, the microchannels were sputtered using a constant dwell time of 1µs and a scanning time of 3mins, with variation in Accelerating voltage and beam current as shown in Table-1.

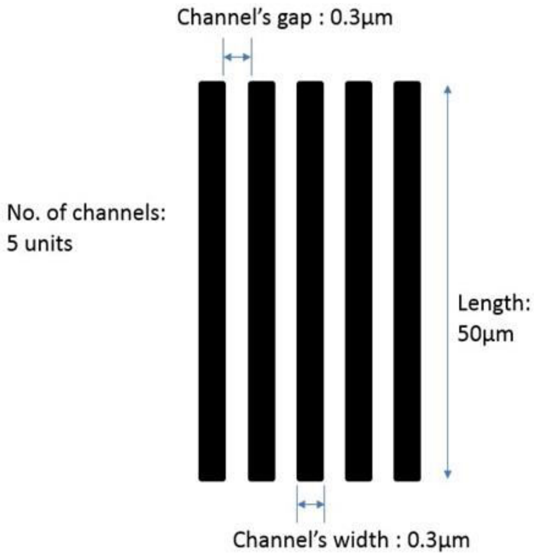

Figure-4. Target pattern for micro-machined.

Table-1. Variation of accelerating voltage and beam current.

Volt. (keV)	Beam Current Available (pA)											
0.5	1.6	6.1	14	23	40	110	180	360	830	2700	5400	12000	22000
1	3.0	5.0	8.0	12	28	73	95	140	380	1100	2000	4200	7400
2	0.0	0.8	3.0	5.0	9.0	23	39	72	190	720	1600	3900	7000
5	0.3	1.3	4.0	7.0	15	41	68	120	360	1600	3500	7700	13000
8	0.5	1.9	6	12	21	66	110	210	620	2000	5000	10000	19000
16	1.0	4.0	11	23	50	150	250	430	1300	5000	11000	25000	42000
30	7.7	24	40	80	230	430	790	2500					

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In the second phase, a Design of Experiment tool utilizing the Central Composite Design (CCD) method was used to determine the range of dwell times and scanning times to be varied. This was found to be in the range of 1-50µs and 3-5mins respectively. The input FIB parameters that were investigated in this work were the beam diameter, beam current, and dwell time. The beam diameter refers to the size of the column opener (nm) that will sputter the ions onto the targeted surface whereas beam current (pA) describes the total amount of charge supplied to the substrate for a given material removed per unit time. The dwell time (µs) is the time for which the beam remains concentrated at a single point on the substrate material and provides ion charges at that point.

Images of the result were captured and qualitatively analysed using a Helios Nanolab G3 SEM. Quantitative analysis was performed using the CCD method. This provides a parameter optimization plot that would advise on the best input FIB parameters to use for attaining the target dimension.

RESULTS AND DISCUSSION

The relationship trend for increasing beam current with target dimensions given varying cases of accelerating voltages are provided in Figures-2, 3, and 4. In all cases, the channel depth is observed to increase when higher beam currents and voltages are applied (Figure-5). The depths are observed to range between 0 to approximately 380 nm. This is as expected since a greater amount of the ions at higher velocities are used when the beam current and accelerating voltage are increased respectively, resulting results in a deeper channel etched into the wafer.

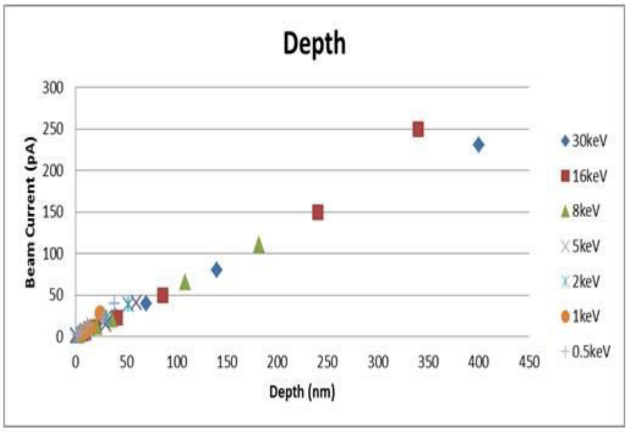

Figure-5. Graph of beam current (pA) versus depth (nm).

The gaps between the channels (Figure-6) were observed to decrease with increasing beam current and accelerating voltage (337.2 – 0nm). This is as expected since the channel width that is sputtered increases (0nm – 683nm) under the same circumstance (Figure-7).

It is noted that the outputs for an accelerating voltage that is less than 5keV could not be observed. In this case surface swelling is observed, whereby the channels combine with one another forming a shallow depression with about 10 nm depth (Figure-8). This observation can also be seen in Figure-9. When a combination of low accelerating voltage and beam current is used (5keV and 7pA), under a dwell time of 1 µs, the ions may not have enough energy and momentum to penetrate the wafer. Hence for low beam currents, a higher accelerating voltage must be used.

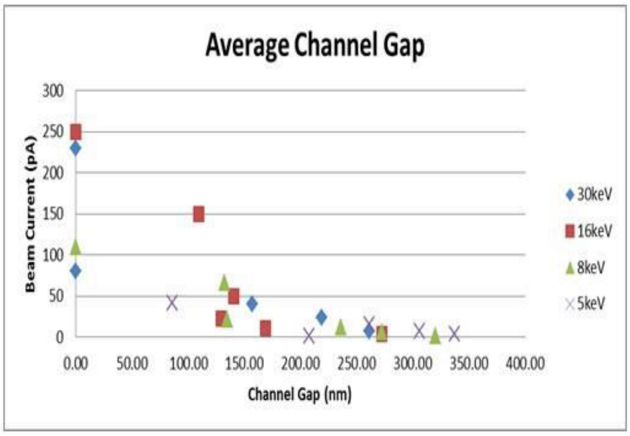

Figure-6. Graph of beam current (pA) versus average channel gap (nm).

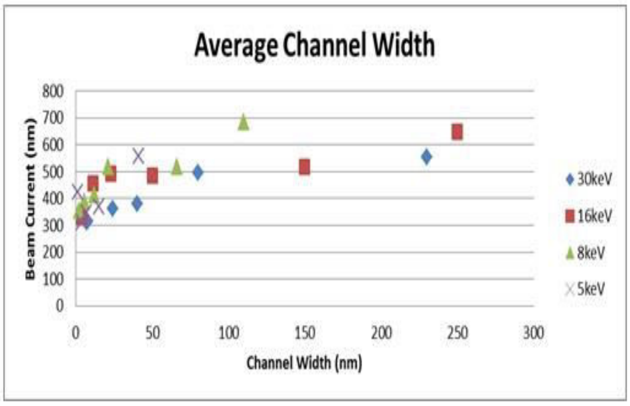

Figure-7. Graph of beam current (pA) versus average channel gap (nm).

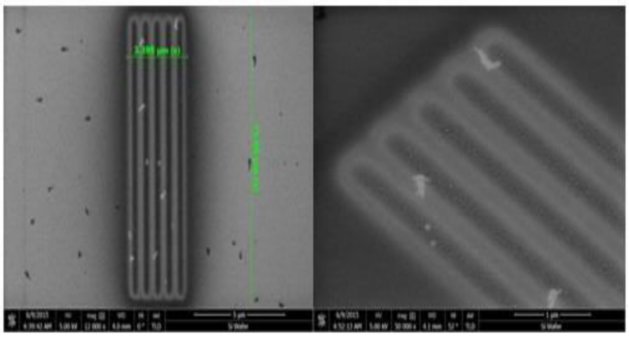

Figure-8. The channels appear to swell and the average channel width and gap between the channels cannot be measured. (Acc. Volt.: 2keV, Beam Current: 5pA).

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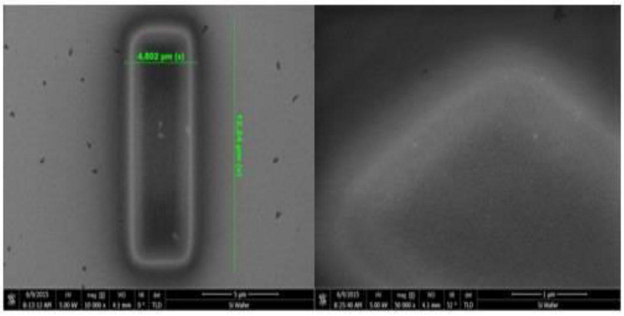


Figure-9. The channels combined forming a shallow 10 nm depth depression. (Acc. Volt.: 1keV, Beam Current: 12pA).

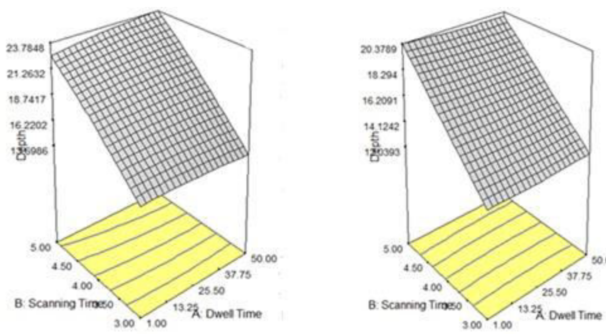
In the second phase of the experiments, the FIB parameters that give the closest result to the target pattern (0.3 μm channel width) are used (Table-2). In this phase, the dwell time and scanning time are varied. It is noted that data for accelerating voltages of 8 and 16 keV have not yet been obtained for the second phase of experiments, at this stage of the research.

Table-2. Selected accelerating voltage and beam current that undergo second phase.

Accelerating Voltage (keV)	Beam Current (pA)	Average Channel Gap (nm)	Average Channel's Width (nm)
30	7.7	261.38	314.76
5	7.0	306.35	346.22

Microchannel depth

Both plots in Figure-10 (a) and (b) show a similar pattern in terms of the effect of scanning and dwell times to the microchannel depth. It appears that the depth increases linearly with increasing scanning and dwell times. The 30 keV accelerating voltage results in a deeper maximum depth (23.78 nm) compared to that produced by 5 keV (20.38 nm).



(a) 30 keV (b) 5keV

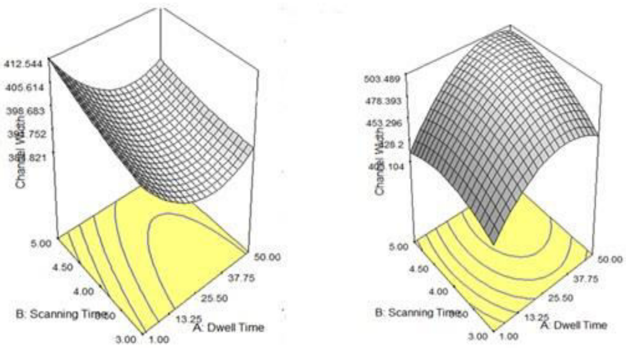
Figure-10. The effect of accelerating voltages to the microchannel depth, at varying scanning and dwell times.

Channel width

Figure-11 (a) shows that for a high accelerating voltage of 30 keV, the results are not as straightforward as the depth plots previously shown in Figure-10. For a given dwell time, there is an apparent linear increase in channel width with increasing scanning times. However, for a given scanning time, the curve plot is quadratic in nature whereby the width decreases to a minimum value with increasing dwell time, but then increases thereafter.

The plot in Figure-11 (b) shows a similar relationship in that for a given dwell time, there is an increase in channel width with increasing scanning times, although this relationship is not linear in nature. However, for a given scanning time, the width increases with increasing dwell times, approaching a certain maximum value before 50 μs. It is interesting to note that at a high accelerating voltage of 30 keV, scanning time appears to play a more significant role in determining channel width. The slope of the surface is markedly steep in this direction as opposed to that in the direction of dwell time.

However, at a low accelerating voltage of 5 keV, dwell time appears to have a more significant role in determining channel width. Increase in channel width is not as significant with increasing scanning time, for a given dwell time. This may be because for a given dwell time, there is not enough energy in the ions to significantly sputter the target, even though the scanning time is increased. However, if the beam is made to stay at a certain spot for a longer time, this will have a more significant effect on the width of the sputtered channel.



(a) 30 keV (b) 5keV

Figure-11. The effect of accelerating voltage to the average channel width, at varying scanning and dwell times.

CONCLUSIONS

Parametric study of sputtering microchannels via focused ion beam (FIB) is carried out to analyse and observe the relationship between the accelerating voltage, beam current, and beam diameter to the depth, channel width and gap between the channels. The clear trend that can be seen is depth and channels width increases (0 – 380nm and 0 – 683nm respectively) when the beam current increases whereas the gap between the channels decreases (337.2 – 0nm). When a combination of low

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accelerating voltage and beam current is used, the Ga+ ions does not appear have enough energy to bombard the silicon wafer surface. For future research, variety of accelerating voltage can be tested to get more precise trend of the depth, channel width, and gap between the channels. In addition, this parametric study can be expanded to see the relationship and the effect of the input parameters to the surface roughness of the sputtered microchannel. The optimization of the parameters also can be found by undergo future analysis.

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