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A novel micro-machining method for the fabrication of thick-film SU-8 embedded micro-channels

Francis E H Tay[1], J A van Kan[2], F Watt[2] and W O Choong[1]

[1] Department of Mechanical and Production Engineering, National University of Singapore, 10 Kent Ridge Crescent, Singapore 119260
[2] Department of Physics, National University of Singapore, 10 Kent Ridge Crescent, Singapore 119260

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Abstract
In this paper, a novel method to realize embedded micro-channels is presented. The presented technology is based on a direct write technique using proton beams to pattern thick-film SU-8. This proton micro-machining method allows the production of high aspect ratio and complex three-dimensional micro-structures in polymers with aspect ratios of over 100 and 20 using poly(methylmethacrylate) (PMMA) and SU-8 respectively. As the SU-8 is used as a structural material, its mechanical properties have to be characterized. For a start, the Young's modulus of the proton beam exposed SU-8 is determined using a stylus-type load–deflection method. The second part of this paper describes the underlying theory and method used by the author to determine the Young's modulus of the proton beam exposed SU-8. Measurements of the SU-8 micro-structures show that the Young's modulus is dependent on the proton beam exposure dose. An exposure dose of 9.5 nC mm^{-2} results in an average Young's modulus value of 4.254 GPa.

1. Introduction

Recent advances in micro-machining fueled by the developments in the electronic and MEMS (microelectromechanical systems) industries have given rise to the advent of various micro-fabrication techniques to fabricate micro-structures made from various materials. There is also a need for fabricating complicated three-dimensional (3D) micro-structures with high aspect ratios, such as micro-channels.

These embedded or open micro-channels find applications in areas such as integrated cooling of integrated electronic circuits (cooling electronics), compact heat exchangers, heat shields and temperature controlled cabinets, fluid distribution systems, hydrodynamic studies of microflows, chemical separation and analysis used in capillary electrophoresis systems, and reactors for modification and separation of biological cells.

Several conventional methods have been successfully used to fabricate micro-channels. Crystal orientation dependent etching is used in producing micro-channels for IC cooling [1] systems. However, this method often requires the bonding of the micro-channels onto the chips, which not only gives rise to complications in subsequent packaging, but is also economically unfeasible. Precision mechanical sawing using a semiconductor dicing saw has also been used to micro-machine micro-channels in silicon, but with limited success [2]. A mechanical method to manufacture channels made of aluminum alloys, copper, stainless-steel and titanium includes the surface shaping of foils, the stacking of foil platelets, the clamping of a foil stack between two cover plates and the assembling of connections [3]. Other suggested methods are reactive ion etching, chemically assisted ion milling, sand blasting, electric discharge machining (EDM), electrochemical machining, laser machining, numerical controlled machining and extrusion [4]. However, all of these require the bonding of the micro-channels with a cover and the shrinkage of the micro-channels upon micro-machining often results in misalignment.

In [4], Youngcheol Joo *et al* combined traditional methods with LIGA [12] to fabricate micro-channels. Guerin *et al* [5] also introduced a simple and low-cost fabrication method to micro-machine embedded micro-channels in SU-8. However, this multi-layer method has several disadvantages. First of all, the walls of the channels are not straight. Second, the SU-8 photoresist undergoes shrinkage during fabrication. Finally,

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the process is complicated with the use of multi-layers.

In this paper, the fabrication of embedded micro-channels in SU-8 photoresist using a direct write [7–9] proton micro-machining method is presented. This method offers flexibility in the design of the micro-channels in a horizontal configuration. In addition, it provides a practical, effective and economical solution to micro-machining embedded micro-channels. Furthermore, the presented method can be easily adapted to the fabrication of other 3D MEMS micro-structures.

The mechanical characterization of the SU-8 micro-structures is also described in this paper. Several methods reported in the literature for the determination of the Young's modulus of thin films are investigated. The first technique is based on resonant frequency testing of vibration structures such as cantilevers or double supported beams [13–15]. However, this method is limited to elastic measurements and the experimental errors can be large. Another method is the bulge test technique that analyzes the deflection of square or rectangular membranes of varying aspect ratios under the influence of a uniform pressure [16, 17]. However, this method fails to provide localized information [18, 19]. Another drawback is the need to handle samples prior to testing. With thin films, it is difficult to avoid the plastic bending or stretching of a sample while removing it from the substrate and mounting it into the test apparatus. The third method is the wafer curvature testing like using a range of coating thicknesses or by varying the temperature [20]. Although the average stress and strain in a film can be measured, the range of stresses is limited by the thermal expansion and/or growth mismatch of the substrate and the film [21–23]. Thus, for a given film and substrate, one cannot dictate the stress to be applied to the film. Furthermore, the measured stress is the average value for a large part of the wafer and this may mask significant local fluctuations. The fourth method is based on sub-micrometer indentation testing. This method allows quick and accurate measurements of hardness, but the large pressures under the indenter may alter the structure of the thin film being tested [24, 25]. Determining the elastic moduli of materials from indentation data is possible, but becomes difficult for hard films. In addition, the influence of the substrate must be considered.

In previous research, the mechanical properties of SU-8 have been investigated [26, 27]. However, these SU-8 micro-structures are produced using near-UV (400 nm) exposure. In the presented Proton Beam Micromachining (PBM) process, the SU-8 is exposed to proton beams of different energies. Subsequently, the mechanical properties are different.

In this paper, a straightforward and easy point-force, load–deflection method to determine the Young's modulus of the SU-8 after exposure to proton beams is also presented. The stylus of the surface profiler scans over cantilevers and double support beams made of SU-8. The profiler records both the stylus force and the deflections the structures. The Young's modulus of the SU-8 is then determined from the classical theory of elastic deflection. The relationship between the Young's modulus of the SU-8 and the exposure dose to a proton beam is also investigated and is presented in this paper.

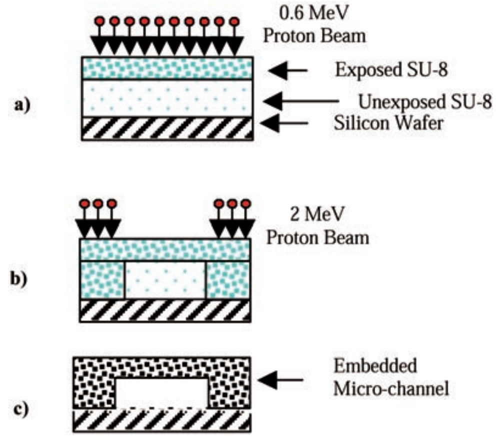

Figure 1. Process for the fabrication of the micro-channel.

2. Fabrication of the micro-channels

A simplified process schematic of the process used to fabricate the monolithic closed embedded micro-channels in SU-8 is shown in figure 1. All the exposure processes for the micro-channels were performed using the nuclear microscope at the National University of Singapore [6]. A proton beam of approximately 1 μm^2 spot size and energies of 0.6 and 2.0 MeV is used. The proton micro-machining scanning system utilizes a Keithley ADD-16 DAC card with a resolution of 12 bits/channel. This corresponds to a grid of up to 4096×4096 pixels, offering increased resolution for the proton micro-machining process [10]. The SU-8 resist layer is first spin coated onto a Si wafer to a thickness of about 34 μm. As SU-8 is a negative-tone resist, the exposed regions will cross-link, which render these regions to be less susceptible to dissolution in the developer. The structures that remain are those that have been exposed to the proton beam. To produce the embedded micro-channels, two exposures were performed, at 0.6 and 2.0 MeV protons. The 0.6 MeV protons have a range of around 10.0 μm in the SU-8 layer and this exposure produced the cover of the embedded channels (figure 1(a)). The walls of the channel were then exposed with the 2.0 MeV protons (figure 1(b)). At 2.0 MeV, the protons can penetrate through the whole SU-8 layer and are stopped in the supporting Si wafer. Proper alignment of the two exposures is achieved by means of a marker on the resist layer, which is mapped using PIXE or RBS signals. The development of the exposed resist followed the following procedure:

(i) put the sample in PGMEA (propylene glycol methyl ether acetate) for 3 min at room temperature;
(ii) take sample out and put it in distilled water for a short time;
(iii) put sample back into the PGMEA for 0.5 min and repeat the cycle for a total time of 7 min inclusive of the first 3 min in PGMEA.

3. Results and applications

Figure 2 shows an embedded micro-channel created using proton micro-machining in the SU-8. There are two reservoirs

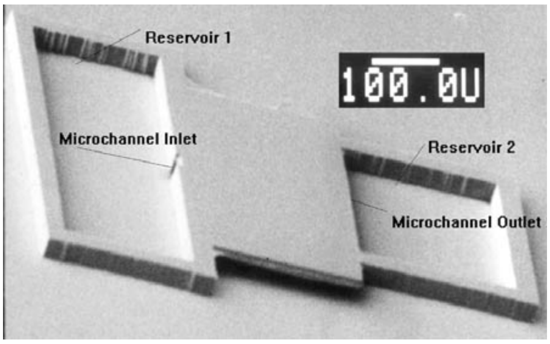

Figure 2. SEM micrograph of fabricated embedded SU-8 micro-channel.

at each side of the channel. The channel is 200 μm long, 15 μm wide and 25 μm deep. The wall angles are 89.6°.

This kind of embedded micro-channel has several applications. One of them is for flow rate detection. Another application is the capillary electrophoresis separation system. Electrophoretic separation is important in chemical and biochemical analysis, particularly for protein analyzing and DNA sequencing. In recent years, a rapid development towards the miniaturization of this technique has taken place in an effort to realize the concept of a miniaturized total analysis system (μTAS) [11]. The main driving force behind this development is the dramatic increase of analysis speed of these miniaturized systems, which can perform an analysis up to a factor of 100 times faster than a conventional system with comparable separation performance.

4. Theory for determination of Young's modulus for proton beam exposed SU-8

The elastic deflection theory (for small deflections) of a cantilever beam with a rectangular cross section is given by

$$\delta = \frac{4FL^3(1-\nu^2)}{Ebt^3} \tag{1}$$

where F is the load applied, L is the effective length, ν is Poisson's ratio, b is the width of the cantilever, E is Young's modulus and t is the thickness of the beam. Equation (1) indicates that the elastic deflection of the cantilever will vary linearly with the force.

The application of the simple cantilever theory to the load–deflection data of beams also enables one to determine the yield strength of the microstructure material. The yield strength is given by

$$\sigma_m = 6LF_m/bt^2. \tag{2}$$

When a force F loads on the center of a fixed–fixed supported micro-bridge with a rectangular cross section, the elastic deflection at this center point is given by

$$\delta = FL^3(1-\nu^2)/16Ebt^3 \tag{3}$$

where F is the stylus force, L is the length of the free-standing part of the fixed–fixed supported micro-bridge, δ is the deflection under the stylus force F, b is the width of one micro-bridge and t is the thickness of the micro-bridge.

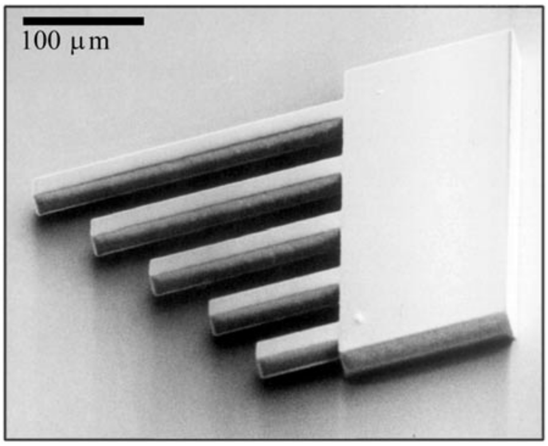

Figure 3. SEM micrograph of SU-8 cantilever microbeams.

5. Experimental procedures

5.1. Sample preparation

All the exposures for cantilevers and double support beams were performed using the nuclear microscope at the National University of Singapore [6], with 1 and 2 MeV proton beams of approximately 1 μm^2 spot size. The resist layer was coated onto the Si wafer using the spin coating technique. The scanning system enables a 2D map to be specified, determining the area over which the beam will be scanned. The thickness of the SU-8 layer is about 34 μm. The samples are exposed to proton beams of two different energy levels such that the depths of the polymer cross linking are different. The 1 MeV protons can reach a range of 21 μm in the SU-8 layer and this exposure creates cantilevers and double support beams. On the other hand, the 2.0 MeV beams can penetrate the whole thickness of SU-8 layer to give the anchors of the micro-structures.

Figures 3–5 are the samples of the SU-8 micro-structures on a silicon wafer.

5.2. Test process

The Alpha-Step 200 surface profiler is used for the experiments. The range of stylus force is from 1 to 25 mg. As the precision of this loading is poor in the lower range of loads, a higher range of loads is used. There are two ways to calibrate the readout of the stylus forces. One is to use a machine that has a calibration system while the second is to calibrate it using a silicon micro-beam of which the Young's modulus is known.

The method adopted is different from that reported in [29]. The force F is fixed so that the deflection δ is a function of microbeam length L. The scan direction is from one end to another end. For cantilevers, it is from the anchor to the free end while for fixed–fixed supported microbridges, it is from one anchor to the other anchor. In [29], the length of the cantilever from the fixed end to the stylus transverse scanning part is difficult to determine. However, the key is to keep the stylus in the center of the cantilever's width. Otherwise it can give some errors. These errors will be discussed in the discussion.

Figures 6 and 7 are plots of the deflection against position using results from the surface profiler.

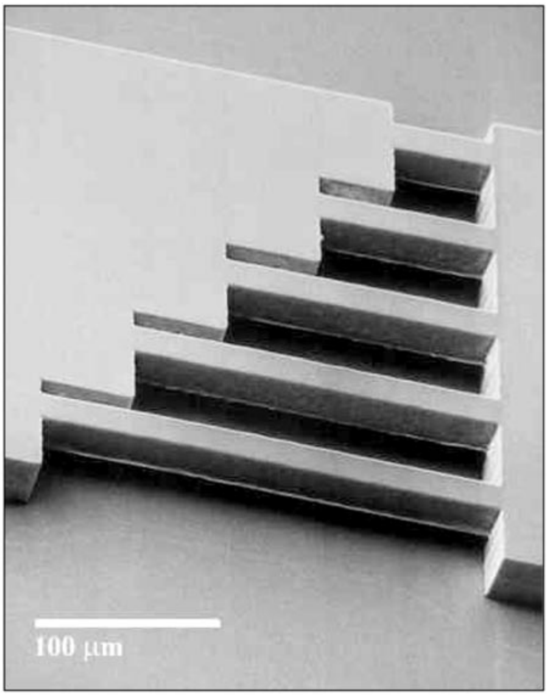

Figure 4. SEM micrograph of SU-8 fixed–fixed supported microbeams.

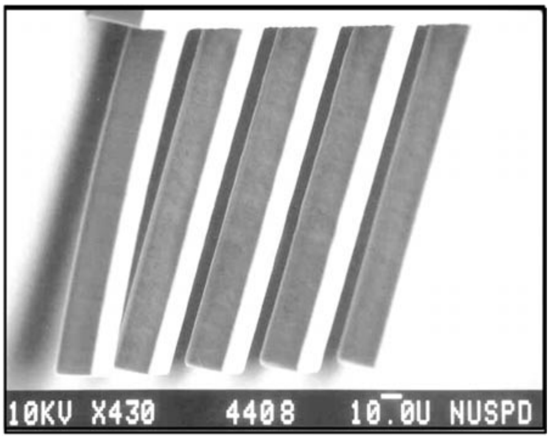

Figure 5. SEM micrograph of SU-8 cantilevers.

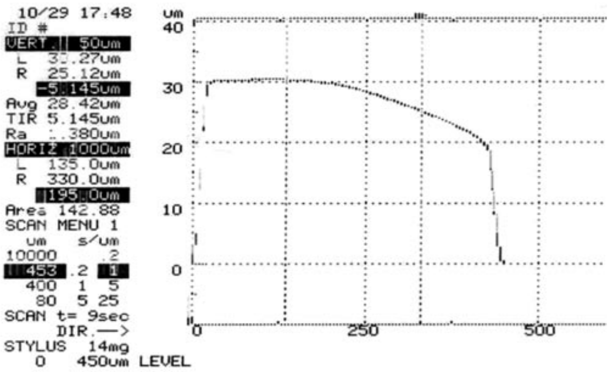

Figure 6. Deflection (micrometres) against position (micrometres) plot generated from the surface profiler for cantilever micro-structures.

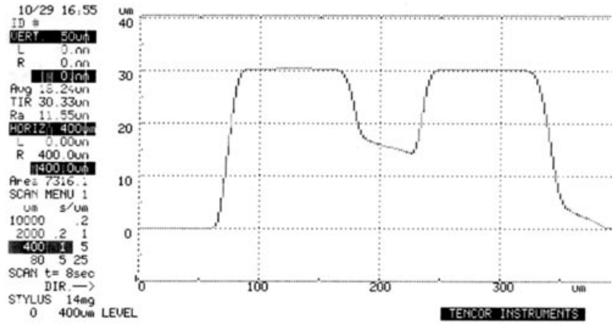

Figure 7. Deflection (micrometres) against position (micrometres) plot generated from the surface profiler for fixed–fixed supported micro-bridges.

Table 1. Experimental Young's moduli for proton doses of 14, 12 and 9.5 nC mm^{-2}.

Proton dose (nC mm^{-2})	Test Case				
	1	2	3	4	5
14	5.31	5.35	5.28	5.28	5.29
12	4.62	4.50	4.55	4.53	4.51
9.5	4.23	4.23	4.30	4.29	4.22

Table 2. Young's moduli of SU-8 against proton exposure dose. In this table FEA denotes Finite element analysis.

	Exposure dose (nC mm^{-2})		
	9.5	12	14
FEA	4.98	5.28	6.15
Test	4.25	4.54	5.31

6. Experimental results

Table 1 shows the test results for SU-8 cantilevers subjected to three different exposure doses. Their exposure doses are 14, 12 and 9.5 nC mm^{-2}. In calculating the measured moduli, a Poisson's ratio of 0.3 was assumed for SU-8. There are five test cases each, and the average values are shown in table 2 which are 5.306, 4.542 and 4.254 GPa, respectively.

From the results, it is obvious that the higher the proton dose, the larger the resulting Young's modulus. Therefore, to obtain a stiffer SU-8 film, the film must have a higher ion dose (assuming that the geometry of the film is the same). A series of a range of doses of 14, 13.7, 12.1, 11.6, 11.0, 9.7, 9.5, 8.1, 7.4, 5.7, 5.6, 3.9, 1.9, 1.0 and 0.9 nC mm^{-2} were used. However, according to the SEM micrographs of the micro-structures, the optimal dose should be around 9.5 nC mm^{-2}. When the dose is too low, the resist will cross-link only partially and, consequently, the cantilevers will collapse onto the silicon substrate. From [25], the bi-axial modulus of elasticity $E/(1-\nu^2)$ for SU-8 after being exposed to UV radiation is 5.18 ± 0.89 dyne cm^{-2}. If ν is 0.3, then E is from 5.5237 to 3.9039 GPa. From [26], the Young's modulus of SU-8 after being exposed to UV radiation is 4.95 ± 0.42 GPa. In [30], the modulus of the SU-8 after being exposed to UV radiation is 4.02 GPa, this was measured with a screw tensile testing machine UTS-100. As a comparison, the test results obtained for SU-8 after being exposed to a proton beam have the same number order as those exposed to UV radiation.

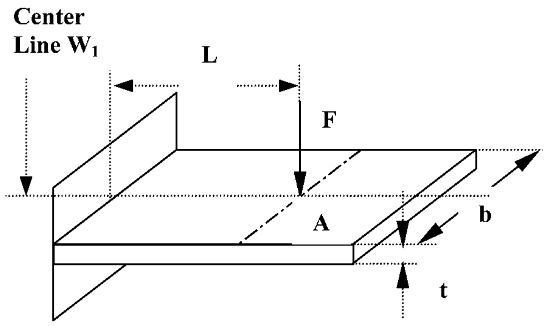

Figure 8. Schematic of the actual micro-cantilever test geometry with the correct stylus scanning path.

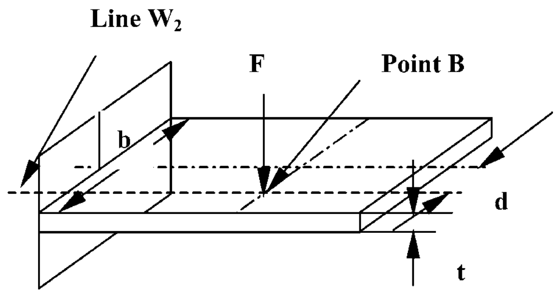

Figure 9. Schematic of actual micro-cantilever test geometry with the wrong stylus scanning path.

From the SEM micrographs of the SU-8 micro-structures (refer to figure 5), it was observed that the films have residual stresses. The residual stress is related to the procedure of spin coating and the ion energy deposition and micro-machining process. The determination of the mechanical strain of the SU-8 after being exposed to the proton beam will be presented in another paper.

As shown in figures 8 and 9, the force F applied by the profiler onto the micro-cantilever scans (moves) from the fixed end to the free end. Figure 8 shows that the stylus moves along the center line W_1 of the cantilever. The deflection δ is then given by equation (1). If the position A, force $\boldsymbol{F}$ and deflection δ are known, the Young's modulus can be obtained using equation (1). During the actual testing of these micro-structures, it is very difficult to make sure that the path is W_1. Figure 9 shows the actual situation for the tests. The stylus scanning path is not W_1 but W_2. The actual deflection δ is then given by

$$\delta = \frac{4FL^3(1-\nu^2)}{Ebt^3} + dtg\frac{24dFL^2}{b^2Gt(t^2+b^2)} \qquad (4)$$

where G is the shear modulus of SU-8 (1.176–1.5092 GPa) and d is the distance between line W_1 and W_2.

For a 12 nC mm^{-2} proton dose and where $L = 195$ μm, $\delta = 5.145$ μm, $F = 14$ mg, $b = 18.5$ μm, $t = 21$ μm and $d = 2$ μm, the relative error is 4.72%. If d is larger, the error will be higher. During the measurements, this error is avoided by scanning several times on one cantilever or fixed–fixed supported bridge and then comparing their plots. Before printing the scanning results, one can also try to scan the micro-structures to make sure that the cantilevers or fixed–fixed supported bridges are parallel to the scanning direction of the stylus.

7. Conclusion

A method for the fabrication of micro-channels with possible applications as a rapid prototyping tool has been presented. With this innovative method, it is possible to micro-machine embedded micro-channels with heights from 5 μm up to 150 μm. The main advantages over previous fabrication methods are better design flexibility and a simplified fabrication process. This process opens the way to the low-cost fabrication of embedded micro-channels and other polymeric structures for use in MEMS applications.

As the resist (SU-8 in this case) is used directly as a structural material, its mechanical characteristics must be determined. In this paper, a convenient and direct method to determine the Young's modulus of SU-8 after exposure to proton beams is introduced. This method uses a surface profiler to measure the stylus load and microstructure deflection. From the load–deflection data acquired during bending, the local elastic modulus of SU-8 was determined without needing to directly handle the samples. To perform the tests, cantilever and fixed–fixed supported micro-bridge samples are prepared by Proton Beam Micromachining using different ion energies for deposition. It is found that the higher deposition dose, the higher the resulting Young's modulus. A suitable dose for micro-structures is 9.5 nC mm^{-2} and the corresponding experimental Young's modulus obtained is 4.254 GPa. This is of the same numerical order as that after being exposed to UV radiation.

A more complete characterization of the mechanical properties will be researched in the future. Using this novel proton beam based micro-machining method and SU-8 (or any other suitable polymer), micro-structures can be fabricated and applied in many fields.

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