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# Proton micromachining: a new technique for the production of three-dimensional microstructures

**J.A. van Kan, J.L. Sanchez, T. Osipowicz, F. Watt**



**Abstract** A novel technique for the fabrication of high aspect ratio three-dimensional (3D) microstructures is presented. A suitable resist (e.g. PMMA or SU-8) is exposed using focused MeV (million electron volt) protons in a direct write process to produce 3D microstructures with sub-micrometer feature sizes. By adjusting the energy of the proton beam, the depth of the microstructures can be controlled very accurately (e.g. between 5 and 160 μm). Single layer SU-8, a newly developed, chemically accelerated, negative tone, near UV, photo-resist, has been used in multiple exposures using different proton energies to produce intricate 3D microstructures. The combination of a well controlled exposure depth coupled with the ability to tilt the sample with respect to the beam increases the manufacturing capability, and allows the production of complex microstructures with well defined edges in single layers of resist.

## 1 Introduction

Only a few techniques are presently available for the production of high aspect ratio 3D microstructures, the best known of which is LIGA. However, because of the high costs involved in such processes (the requirements of a synchrotron accelerator and complicated mask production process) there is a need for cheaper 3D microstructure fabrication techniques. Particularly in the design stage, it is useful to produce prototypes both rapidly and inexpensively. One of the techniques recently developed for such purposes is stereo microlithography which allows the manufacture of 3D parts by a light-induced spatially resolved polymerization process (Ikuta and Hirowatari, 1993). A limitation of this technique is its rather low accuracy (Bertsch et al., 1997; Bertsch et al., 1998).

In order to develop 3D lithographies which do not require a high flux of soft X-rays only available from a synchrotron, new types of resist are being developed. One of these is SU-8 (Lorenz et al., 1996), a chemically amplified negative tone resist which shows high potential because it can be used with UV radiation and proton micromachining (van Kan et al., 1999a; van Kan et al., 1999b). SU-8 has been used to produce microstructures with thicknesses up to a few mm.

In this paper, proton micromachining will be shown to be a powerful tool in the production of detailed 3D microstructures suitable for rapid prototyping and the manufacture of molds and stamps. In proton micromachining a MeV proton beam, focused down to sub-micrometer dimensions, is directly scanned across a resist. Such a direct write process has the advantage that a mask is not required to produce structures with high aspect ratios and sub-micrometer detail in the lateral directions (Springham et al., 1997; Sanchez et al., 1998; van Kan et al., 1999a). Proton micro-machining has therefore high potential for rapid prototyping.

In this paper the following points will be addressed: Firstly we will compare the positive resist PMMA with the negative resist SU-8 with respect to proton beam exposure. The SU-8 layers were deposited using spin-coating technique on Si wafers and have thicknesses up to 36 μm. Secondly examples of 3D microstructures produced with proton micromachining in both resists will be shown. Thirdly multiple exposures will be discussed: These multiple exposures can be used to produce multi level structures in single layers of resist using different proton energies. By changing the angle of the resist with respect to the beam, complex non-prismatic shapes with sharp well-defined edges can be produced using multiple exposures.

## 2 Experimental procedures

The lithographic work was carried out using the nuclear microscope at the Research Centre for Nuclear Microscopy at the National University of Singapore (Watt et al., 1994), where 100 nm spot sizes can be achieved for 2.0 MeV protons (Watt et al., 1998). Typical currents used for micromachining range between 1 and 100 pA with a typical spot size of 1 $\mu m^2$. Details of the scanning system used for proton micromachining can be found elsewhere (van Kan et al., 1999a; Sanchez et al., 1998). All the exposures were performed in an area of $400 \times 400$ $\mu m^2$ using a grid

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of 512 × 512 pixels. The dose required for a full PMMA exposure corresponds to 100 nC/mm$^2$ whereas the more sensitive SU-8 requires only 10 nC/mm$^2$ (van Kan et al., 1999b).

Presently the exposures are performed using a belt driven van de Graaff accelerator. This type of accelerator in general exhibits poor energy stability and consequently produces proton beams with wide intensity fluctuations (typically in the tens of Hz frequency range). Therefore, in order to achieve accurate exposure doses, we employ two types of beam normalisation procedures: (a) normalization of the dose/pixel using backscattered protons for direct normalization (Sanchez et al., 1998) or (b) measurement of the total beam charge in a rapid and multiple repeating (typically more than 100) scanning procedure (van Kan et al., 1999). This last method is more suitable for sensitive resists such as SU-8 which require a much lower proton dose than the more conventional PMMA. These normalization procedures will be made redundant when proton micromachining exposures are carried out using a state-of-the-art high stability 3.5 MV HVEE Singletron accelerator to be installed in September 1999 at the Research Centre for Nuclear Microscopy.

Multiple exposures, performed with different proton energies or at different incident angles allow the production of angled structures with a pre-determined depth. Alignment between multiple exposures is achieved by means of a marker on the resist layer, which is mapped using Particle Induced X-ray Emission (PIXE) or backscattered protons (RBS).

## 3
## Results

Figure 1 shows a series of cogs made in a thick piece (2 mm) of PMMA resist using a 2.0 MeV proton beam with a spot size close to 1 μm$^2$. The beam dose per pixel was controlled using proton backscatter normalization. The cogs have a height of 63 μm, which corresponds to the range of 2.0 MeV protons in PMMA.

The bottom left cog has become detached from the bulk PMMA, probably weakened structurally due to the spread of the beam at the end of range. The largest aspect ratio of the cogs in Fig. 1 is about 20. Although high aspect ratios are difficult to obtain in thick PMMA because of the end of range beam broadening, high aspect ratios approaching 100 can be achieved in thin resist layers or suspended cantilevered structures (Sanchez et al., 1998).

Figure 2 shows five cantilever structures produced in a single 36 μm thick SU-8 layer applied on a Si wafer. Two exposures were performed with 1.0 and 2.0 MeV protons. The 1.0 MeV protons have a range of about 22 μm in the SU-8 layer and therefore 1.0 MeV protons were used to produce the cantilevers. The supporting anchor was exposed using 2.0 MeV protons, which penetrated through the SU-8 layer into the substrate. The cantilevers have a length between 70 and 260 μm, a width of 20 μm and a height of 22 μm.

Figure 3 shows an example of an intricate multilevel anchored grid structure made by proton micromachining. This structure was produced using 3 different proton energies in one single layer of resist. In Fig. 3a an overview of the complete structure is shown. At the centre of the structure, two anchors produced using 2.0 MeV protons can be observed. Figure 3b shows the white dotted region in Fig. 3a and c is a schematic overview of the supported multilevel grid. Protons with an energy of 600 keV have a range of less than 10 μm in SU-8; this energy was used to produce the shallowest structures. The walls perpendicular to the first set were exposed with a 1.0 MeV proton beam resulting in 22 μm walls. The individual lines have a width of 5 μm and a spacing of 20 μm. The grid is suspended by the two anchors,

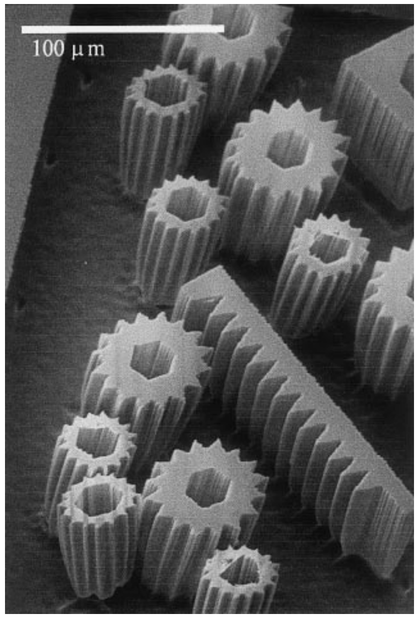


**Fig. 1.** SEM micrograph of cogs produced in bulk PMMA using a direct-write 2.0 MeV proton beam



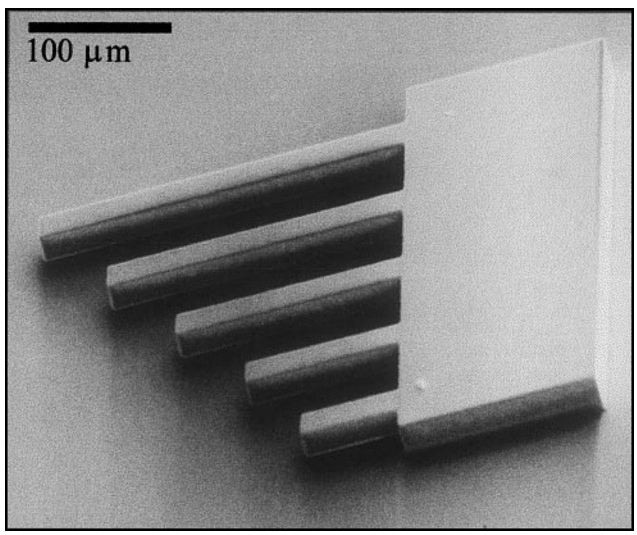


**Fig. 2.** SEM micrograph of a set of cantilevers produced in a 36 μm thick SU-8 layer. The suspended cantilevers were produced using a 1.0 MeV proton exposure and the anchor was exposed using 2.0 MeV protons

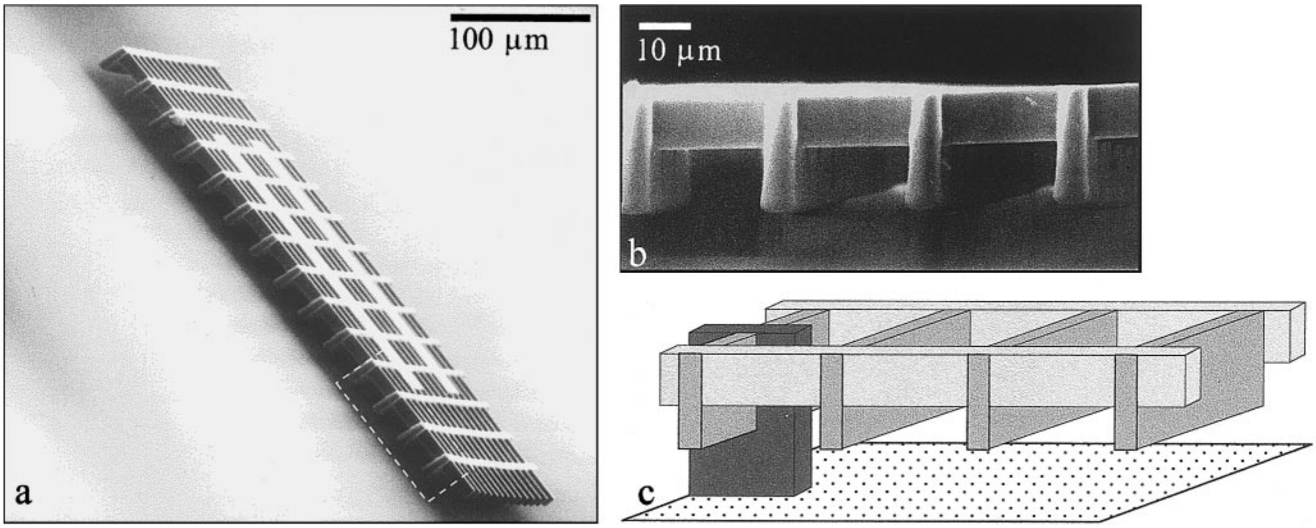


**Fig. 3.** SEM micrograph of a suspended multilevel grid produced in one 36 μm thick layer of SU-8 resist using three exposures at proton energies of 0.6, 1.0 and 2.0 MeV

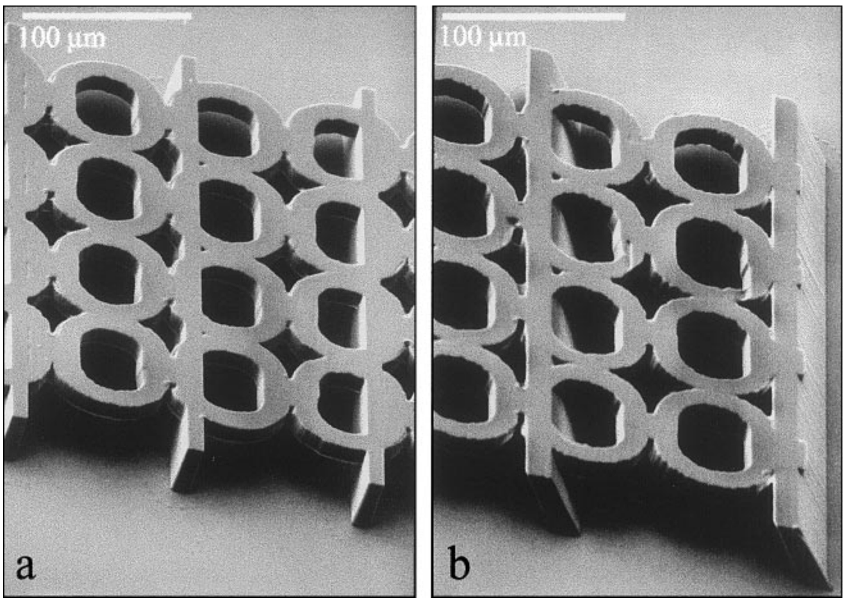


**Fig. 4.** SEM micrograph of self supporting circular structures anchored to a set of perpendicular (left) and 40° tilted (right) walls. A single 36 μm thick layer of SU-8 resist was used in two exposures at proton energies of 0.6 MeV and 2.0 MeV

$50 \times 200\ \mu m^2$ each. Typical exposure time for the whole structures is 40 seconds using a current of 100 pA.

Figure 4 shows a double layered structure produced in a 36 μm layer of SU-8. The top layer was produced using 600 keV proton beam exposure. The top layer is a circular type of structure with straight segments; the walls have a width of 15 μm and a height of almost 10 μm. These circular structures are supported by straight walls which were produced using a 2.0 MeV proton beam. These walls have a length of 380 μm and a width of 10 μm. In Fig. 4a (left) the 2.0 MeV proton beam was aligned perpendicular to the resist, parallel to the 600 keV exposure. In the second structure shown in Fig. 4b (right), the sample normal was tilted at an angle of 40° to the proton beam.

In Fig. 4a (left) the top structure was produced using a special scanning algorithm: The proton beam was first raster scanned over the required pattern, followed by a scan which separately scanned the outline of the figure. This procedure had the effect of sharpening the structure (compare the structure in Fig. 4a with the structure in Fig. 4b where the outline scan was not implemented). These special exposure procedures will become redundant when proton micromachining is performed using the new HVEE Singletron accelerator.

## 4 Conclusions

In proton micromachining the proton beam can be focused down to sub-micrometer dimensions and directly scanned across a resist, thereby eliminating the need for a mask. High aspect ratios (close to 100) can be achieved. Although this procedure is generally slower than masked processes for bulk production, it is very suitable for rapid prototyping and the manufacture of molds and stamps.

The proton beam has a well defined range in resist (unlike X-rays), and therefore the depth of structures can be easily controlled by using different proton energies, enabling the construction of slots, channels, holes etc. with a well defined depth. The depth can be different for slots, channels or holes in one single resist layer.

In the near future, a more stable, 3.5 MV accelerator will be utilised. This new feature will increase the capability of proton micromachining at the Research Centre for Nuclear Microscopy: Structures of increased depth of up to 160 μm will be produced with 3.5 MeV protons, coupled with improved definition in walls and edges consistent with increased beam intensity stability.



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