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Nickel and copper electroplating of proton beam micromachined SU-8 resist

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Abstract Proton beam micromachining (PBM) has been shown to be a powerful technique to produce three-dimensional (3D) high-aspect-ratio microstructures (Watt et al., 2000). Potential commercial applications of PBM, which is a fast direct write technique, will become feasible if the fabrication of metallic molds or stamps is realised. Metallic components can be produced by electroplating a master from a microstructure produced in resist. The production of high-aspect-ratio metallic stamps and molds requires a lithographic technique capable of producing smooth and near 90° sidewalls and a one to one conversion of a resist structure to a metallic microstructure. PBM is the only technique capable of producing high-aspect-ratio microstructures with sub-micron details via a direct write process. In PBM, SU-8 (Lorenz et al., 1997) resist structures are produced by exposing the SU-8 resist with a focused MeV proton beam followed by chemical development and a subsequent electroplating step using Ni or Cu. The data presented shows that PBM can successfully produce high-aspect-ratio, sub-micron sized smooth metallic structures with near 90° sidewall profiles.

1
Introduction

Current microelectronics production technologies are essentially two-dimensional (2D), well suited for the 2D topologies prevalent in microelectronics. For the proposed development of MEMS devices and their integration with microelectronics however, high-aspect-ratio three-dimensional (3D) microstructures with sub-micron details are also of growing interest. It is therefore essential to develop new lithographic techniques suitable for the production of high-aspect-ratio microcomponents. One of the more established techniques for 3D micromachining is LIGA (Cerrina et al., 1997), although one deterrent for this process is the relative high production cost involved coupled with the scarcity of facilities. There are a few emerging new lithographies (e.g. proton beam micromachining (PBM), DUV lithography and stereo microlithography). PBM is being developed at the Research Centre for Nuclear Microscopy (RCNM) and has shown to be a promising new 3D lithographic technique (Watt et al., 2000; van Kan et al., 2000). In PBM, a high energy (e.g. 2 MeV) proton beam is focused to a sub-micron spot size and scanned over a resist material (e.g. SU-8 and PMMA). When a proton beam interacts with matter it follows an almost straight path, the depth of which is dependent on the proton beam energy. PBM is a fast direct write lithographic technique; in a few seconds a complicated pattern in an area of $400 \times 400\ \mu m^2$ can be exposed down to a depth of 150 μm. These features make PBM a direct write technique of high potential for the production of high-aspect-ratio structures with sub-micrometer detail in the lateral directions at a much lower total cost than the LIGA process, which requires a synchrotron radiation source and precision masks. PBM has therefore high potential for rapid prototyping.

Research is currently under way to improve the process that employs the negative photo-resist SU-8 as a mold to electroplate Ni and Cu. In this paper current electroplating results at the RCNM of PBM produced SU-8 microstructures are discussed, and in these experiments we have produced microstructures in nickel with a width of 300 nm and a height of 15 μm. PBM can therefore be used as a powerful tool in the production of detailed high-aspect-ratio 3D microstructures, suitable for the manufacture of molds and stamps.

2
Experimental procedures

Protons with a typical energy of 2.0 MeV from a nuclear accelerator are focused down to sub-micron spot sizes and then magnetically scanned over a resist material to write a 3D pattern in the resist. The recent introduction of a state of the art, high brightness, 3.5 MV single-ended accelerator (HVEE Singletron) has improved PBM substantially. This new proton accelerator produces proton beams of much higher stability in energy and intensity than the belt driven Van de Graaff accelerator previously used for micromachining purposes. A schematic overview of the PBM facility used at the Research Centre for Nuclear Microscopy (RCNM), National University of Singapore is

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shown in Fig. 1. The 90° magnet is used to stabilise the energy of the protons produced by the accelerator, and by utilizing a switcher magnet, multiple beam lines can be served. In Fig. 1 beam line facilities are shown. The nuclear microscope is connected to the 30° port of the switcher magnet and is currently in use for multidisciplinary research, including the prototype proton beam micromachining, at the Research Centre for Nuclear Microscopy. Using this facility, 100 nm spot sizes can be achieved for 2.0 MeV protons (Watt et al., 1998). The second line, connected to the 10° port of the switcher magnet, is under construction, and will be the first dedicated PBM facility worldwide.

Typical currents used for micromachining range between 1 and 100 pA with a typical spot size of 0.5 × 0.5 μm^2. In the experiments described here a 2 MeV proton beam was used. Details of the scanning system used for proton beam micromachining can be found elsewhere (Bettiol et al., 2001). Typically, areas from 400 × 400 μm^2 to 2 × 2 mm^2 were exposed using a proton beam magnetically scanned in a digitized grid up to 4096 × 4096 pixels.

An accurate exposure dose per pixel was achieved in two ways: (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 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. In both normalization methods the beam is moved from pixel to pixel with a typical pixel dwell time of about 0.1 to 1 ms per pixel. To allow the production of smooth sub 100 nm sidewalls of high-aspect-ratio, new normalization methods are being developed and smaller pixel sizes will be implemented.

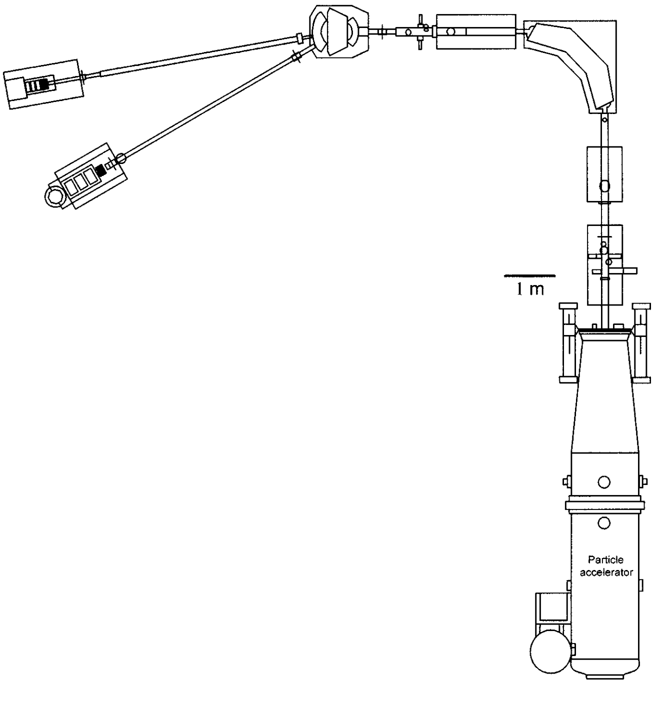

Fig. 1. Schematic diagram of the new proton beam micromachining facility (10° beam line) and the existing nuclear microscope (30° beam line)

A crucial step in the development of mechanically strong microstructures for molds and stamps is the conversion of the mechanically weak structures made from ploymer material to metallic microstructures. The conversion to metallic structures has been performed using three different types of electroplating baths. The Cu electroplating was performed in a standard Cu sulfate bath (Lowenheim, 1978) and a Cupracid^{R} HT bath. The Ni was produced using a modified Watts bath (Lowenheim, 1978). In these preliminary tests, SU-8 layers of about 20 μm were applied on two different Si wafers. One wafer was pre-coated with a 130 nm layer Cu, and the other wafer was pre-coated with 25 nm Ti followed by a 200 nm Ni coat. Here the Cu and Ni act as seed layers for plating and the Ti as an adhesive layer to bond to the Si wafer (Romankiw and O'Sullivan, 1997). After development, the areas between the SU-8 structures were typically electroplated up to a thickness of 10–18 μm. The SU-8 was subsequently removed with SU-8 remover (nano remover PG^{TM}). Typical plating currents for Cu and Ni were 25 and 50 mA/cm^2, respectively.

3
Results

In the first example, two sets of identical square pillars were produced using proton beam machining, see Fig. 2. The first set was prepared in a 30 μm thick SU-8 layer on a Si wafer, the second set was prepared in a 20 μm thick SU-8 layer on a Si wafer with the Cu seed layer for plating. The squares presented here have more precise rectangular corners compared to our earlier results (van Kan et al., 2001). The difference can be explained because in previous experiments the settling time in the magnetic scanning system was chosen too short. Typical pixel dwell time used in earlier experiments was 0.1 ms per pixel, whereas in these new experiments a pixel dwell time of 1 ms was chosen. In order to reduce the exposure time in future PBM experiments while maintaining sub-micron sharpness in the edges of the structures an electrostatic scanning system will be implemented in the new PBM facility at the RCNM. The squares were exposed using 2 MeV protons with a typical spot size of 0.5 × 0.5 μm^2, and a pixel size of 0.4 × 0.4 μm^2. Figure 2a shows a higher magnification electron micrograph of one of the SU-8 pillars and Fig. 2b shows an overview of the SU-8 pillars. A corner of one of the pillars in Fig. 2a shows a curvature of about 0.5 μm, which matches closely the beam spot size. In Fig. 2c the result of using a set of pillars as a mold for Ni plating is shown. It is clear all the SU-8 has been removed and the Ni grid has corners with similar sharpness compared to the SU-8 pillars.

In Fig. 3a we see the RCNM logo next to a set of parallel lines with decreasing distances. This exposure was performed with 2 MeV protons in a 30 μm thick layer of SU-8 applied on a Si wafer. In Fig. 3b the SU-8 structure similar to the one in Fig. 3a was used as a mold for Ni plating. The SU-8 was applied on the Cu seed layer. The SU-8 was successfully removed after 15 μm Ni electroplating. As can be seen in the insert of Fig. 3b the narrowest Ni line has a width of 300 nm, this corresponds to an aspect ratio of around 50. Both the logo and the lines were exposed using

0.4 × 0.4 μm^2 pixel size. The lines have a length of 190 μm, while maintaining a constant width over the whole length the narrowest line has become fragile as can be seen in the top left corner of Fig. 3b.

In Fig. 4 three sets of circles are shown. Figure 4a shows circles produced in 30 μm thick SU-8. In Fig. 4b and c, Ni and Cu plated circles are shown; they were produced in a modified Watts bath and a standard Cu sulfate bath respectively (Lowenheim, 1978). All the 3 sets of circles have smooth sidewalls. The top surface of the SU-8 and the Ni is smooth, whereas the Cu has a rough top surface.

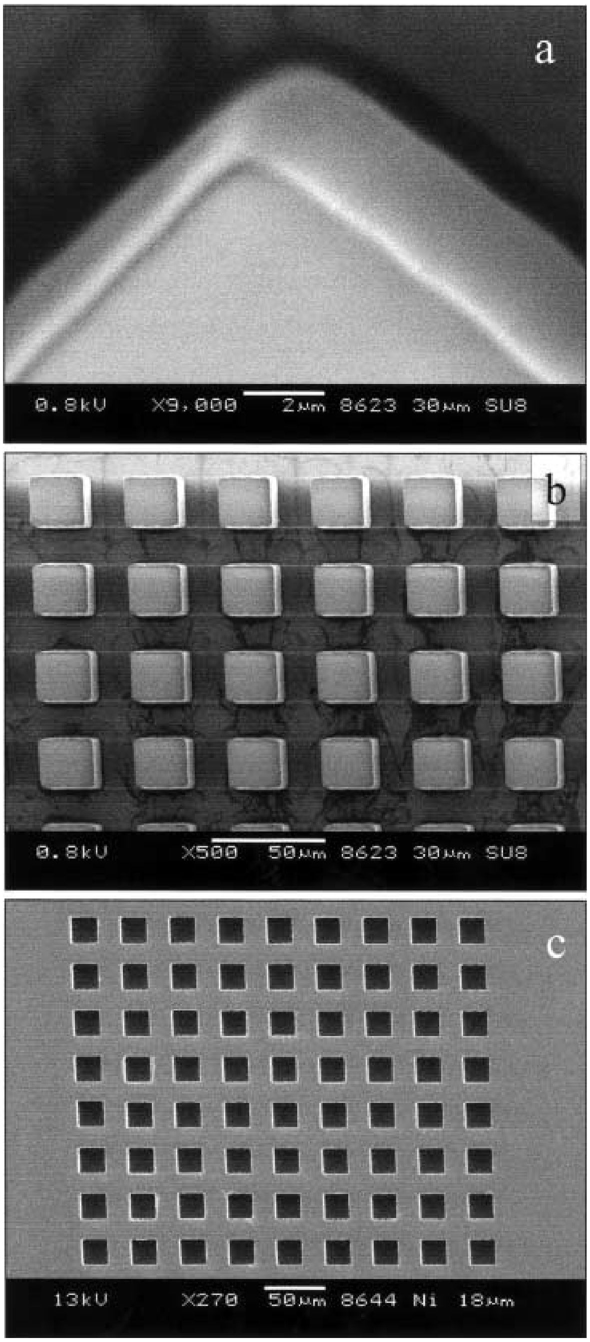

Fig. 2a–c. In **a** and **b** SEM micrographs of pillars produced in 30 μm thick SU-8 on a Si wafer are shown. The pillars have a size of 20 × 20 μm^2. A SEM micrograph of a 18 μm thick Ni grid produced using PBM is shown in **c**

In Fig. 5a and b two sets of plated Cu grids using the standard Cu sulfate bath and the Cupracid^R HT bath are shown respectively. In both cases the sidewalls are smooth but in the case of the Cupracid^R HT bath also the top surface has a high degree of smoothness. The Cu grid in Fig. 5a was plated on the Cu seed layer whereas the Cu grid in Fig. 5b was plated on the Ni/Ti seed layer. During removal of the SU-8, delamination of the plated Cu layer was encountered. It is worth noting that the Cu grid in Fig. 5a was produced with a pixel dwell time of 0.1 ms, which caused rounded corners.

4
Conclusions

In PBM the proton beam can be focused down to submicrometer dimensions and directly scanned across a resist, thereby eliminating the need for a mask. Arbitrary shapes can be fabricated e.g. squares with sharp corners or near perfect circles. High-aspect-ratios (close to 100) can be achieved in PMMA resist (Sanchez et al., 1998). Smooth plating results were obtained for Ni and Cu with near perfect sidewalls and smooth top finish. The SU-8 removal rate after plating was close to 100%. Cu plating needs to be optimized further to ensure good adhesion of the microstructures to the Si substrate. Here we have demonstrated the construction of state-of-the-art plated PBM microstructures with an aspect ratio of 50 for a Ni wall of 300 nm wide and 15 μm high. The scanning speed in the

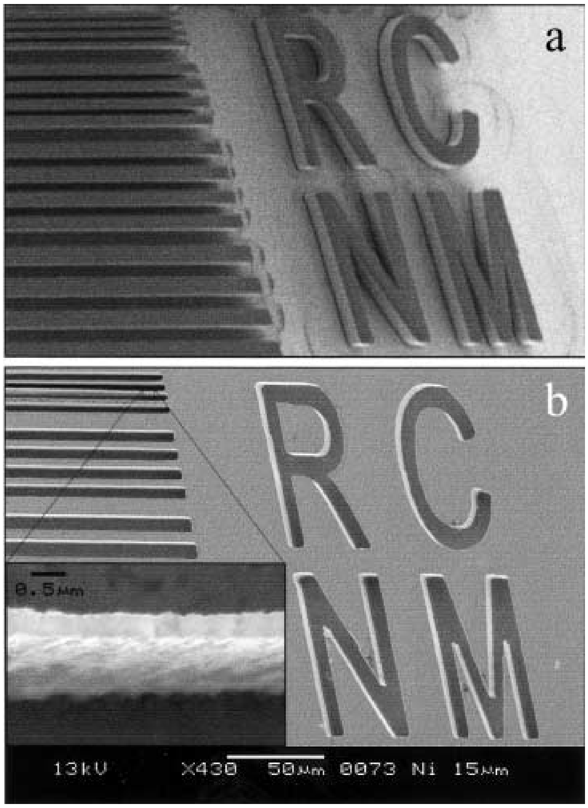

Fig. 3. a SEM micrograph of the RCNM logo with a series of narrow lines and spaces produced in 30 μm thick SU-8. In **b** the template in **a** is used as a mold to plate 15 μm Ni. The inset shows the narrowest line which has a width of 300 nm, corresponding to an aspect ratio of 50

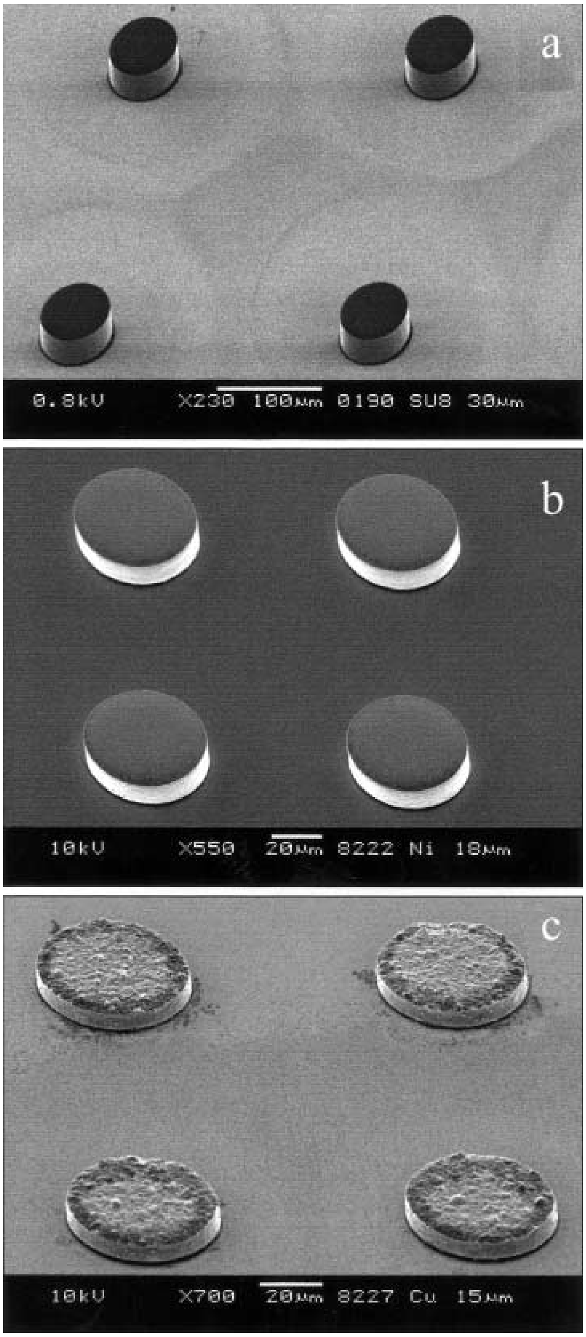

Fig. 4a–c. SEM micrograph of polymer and metal plated circles. **a** SU-8 circles produced in 30 μm thick SU-8, **b** 18 μm thick Ni plated using the modified Watts bath and **c** 15 μm thick Cu plated using the standard Cu sulfate bath

new PBM facility is expected to increase by a few orders of magnitude with the introduction of an electrostatic scanning system, avoiding the long settling times needed in the prototype magnetic scanning system. Although the PBM procedure is generally slower than masked processes for bulk production, it is very suitable for rapid prototyping, and with the successful introduction of electoplating we have demonstrated that the field of potential applications for PBM can be extended through the manufacture of molds or stamps for batch production.

The introduction of the new 3.5 MV Singletron proton accelerator has enabled the production of smooth well defined microstructures. In the near future new exposure normalization procedures will be developed together with the introduction of an even more powerful quadrupole lens system for focusing protons. The production of sub 100 nm structures is expected to become reality soon in a dedicated PBM set-up.

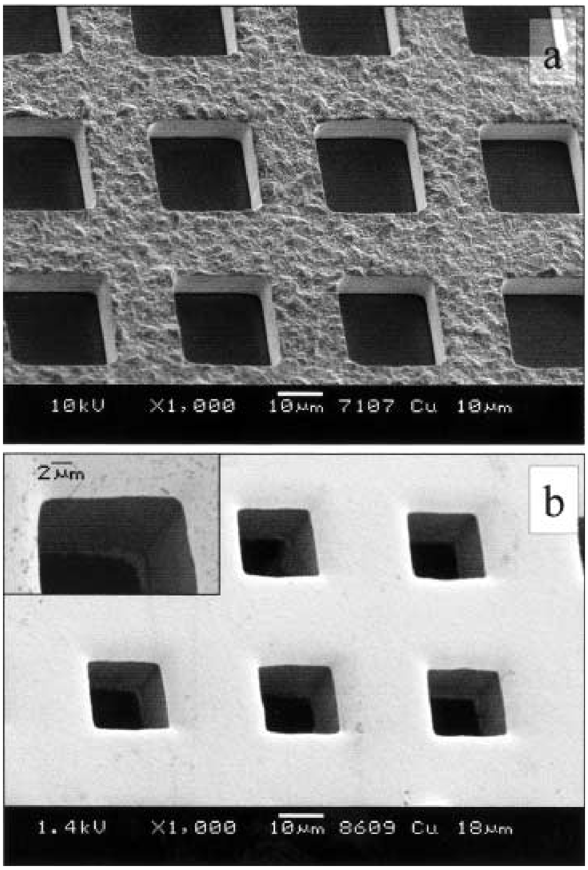

Fig. 5a, b. SEM micrograph of plated Cu grids: **a** Plated for 10 μm using a standard Cu sulfate bath and **b** Plated for 18 μm using a Cupracid^R HT bath

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