ELSEVIER

Sensors and Actuators A 92 (2001) 370–374

SENSORS AND ACTUATORS A PHYSICAL

www.elsevier.com/locate/sna

Proton beam micromachining: a new tool for precision three-dimensional microstructures

J.A. van Kan*, A.A. Bettiol, B.S. Wee, T.C. Sum, S.M. Tang, F. Watt

Physics Department, Research Centre for Nuclear Microscopy, National University of Singapore, Lower Kent Ridge Road, Singapore 119260, Singapore

Abstract

Proton beam micromachining (PBM) is a novel technique for the production of high aspect-ratio three-dimensional (3D) microcomponents. PBM is a direct write process in which a focused beam of MeV protons is scanned in a pre-determined pattern over a suitable resist material (e.g. PMMA or SU-8) and the latent image formed is subsequently chemically developed. One strategy for full exploitation of the advantages offered by PBM is the conversion of the microstructures produced in the resist to metallic components by electrolytic plating. The metallic structures may then be used in a bulk production process, e.g. microstamping or micromolding. In this paper we describe the introduction of a beam blanking system to improve the quality of microstructures, and present data showing that electrolytic Ni plating of proton beam micromachined resist structures result in well defined and smooth metallic microstructures.

PACS 07.10.Cm; 07.78.+s; 85.40.Hp

Keywords: Micromachining; High aspect ratio; Nuclear microscope; Proton beam; Plating

1. Introduction

The last decade has seen rapid growth in micro-electro-mechanical systems (MEMS) technology. The current production processes mostly utilize the well-established, but essentially two-dimensional (2D), optical lithography. Developing techniques to make true three-dimensional (3D) microstructures will enhance the potential of MEMS. The LIGA [1] process has 3D capability, but it requires precise X-ray masks and a bright X-ray source, typically a synchrotron accelerator. Several other 3D processes are under development, e.g. deep UV lithography, stereo microlithography and proton beam micromachining (PBM), a process that uses a focused MeV proton beam to produce a 3D latent image in a resist material [2,3]. Of these techniques, PBM is the only technique that offers the capability of producing direct-write sub-micron sized high aspect-ratio structures.

MeV protons impinging on a resist material lose energy mainly through collisions with atomic electrons. The proton trajectory is essentially unaltered by these interactions due to the large mass ratio between protons and electrons ($m_p/m_e \sim 1800$), except at the end of range where large angle scattering occurs due to the increased incidence of nuclear collisions. Furthermore, the energy deposition induced by the interactions of protons with the material does not vary appreciably with the proton energy, therefore the energy deposition along the path is almost uniform. Unlike an e-beam exposure, where the electron trajectories are erratic due to multiple large angle collisions, 2 MeV protons undergo a straight path and therefore have a well-defined range in resist depending on their energy, e.g. 2 MeV protons have a range of 62 μ in PMMA. As a result, multiple exposures at different energies allow the production of complex multi-layer microstructures, e.g. buried micro-channels in one single layer of resist [4]. Microstructures with aspect ratios approaching 100 have been produced with sub micrometer detail in the lateral direction [5].

One niche area for PBM is the production of 3D molds and stamps, for which it is necessary to make metallic or ceramic replicas of the resist microstructures. In this paper, the quality of microstructures produced using the PBM technique has been improved with the addition of a new beam blanking system into the scanning system. The beam blanking system will be described, together with preliminary results on electrolytic Ni-plating of proton beam micro-machined 3D SU-8 [6] structures.

* Corresponding author. Tel.: +65-874-2624; fax: +65-777-6126; URL: http://www.nus.edu.sg/NUSinfo/RCNM/index.htm.
E-mail address: phyjavk@nus.edu.sg (J.A. van Kan).

0924-4247/01/$ – see front matter
PII: S0924-4247(01)00574-X

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 [7], where 100 nm spot sizes can be achieved for 2 MeV protons [8]. Beam currents used for direct write proton beam micromachining range between 1 and 100 pA with a typical spot size of 1 μm^2. More details of the scanning system used for proton beam micromachining can be found elsewhere [4,5]. During exposures the beam is scanned over the resist using a set of electromagnetic scan coils. The electromagnetic scan coils can move the proton beam over the sample with a maximum speed of about 8 nm/μs, which is limited by the response time of the scan coils used in our system. For the exposure of multiple uncoupled structures, we have previously relied on the rapid movement of the beam between exposures. This has necessarily led to a low but unwanted proton dose during the beam positioning. While this has not been a problem when using the resist PMMA, in the case of chemically amplified resist such as SU-8, the unwanted dose results in poor definition in the microstructure edges after development of the resist, as shown in Fig. 1a. To prevent the deposition in the sample of any unwanted dose we have introduced a beam blanking system, where the beam is deflected out of the normal beam path using the field generated between a set of electrostatic plates. For example, for a 10 μm jump in beam position, a blanking time of 1.25 ms is required to allow the scan coils to reach the desired field. During blanking, the scan coils field is changed at the same rate used in exposing figures. The switching time for blanking is typically less than 1 μs. The improvement established with the new blanking system is clearly visible in Fig. 1b. The current scanning system is based on a Keithley ADD-16 DAC card, which has 16 DACs of a resolution of 4096×4096 (12 bits) and a minimum pixel dwell time of 20 μs. A typical exposure is performed in an area of $400\,\mu m \times 400\,\mu m$. The dose required for a full PMMA exposure corresponds to 100 nC/mm^2 whereas the more sensitive SU-8 requires only 30 nC/mm^2 [9].

A typical exposure rate for SU-8 in the current system is about 1500 s/mm^2. In an optimised set-up the exposure time can be significantly reduced by the installation of an electrostatic scanning system, which avoids the long settling times necessary in the current magnetic scanning system. Exposure rates controlled via electrostatic scanning are expected to be as fast as 20 s/mm^2, while still maintaining micrometer resolution in the lateral direction.

Up to now the PBM exposures have been performed using a belt driven van de Graaff accelerator and this type of machine exhibits intensity fluctuations, typically in the tens of Hz frequency range. There are two ways of reducing the effect of the beam intensity fluctuations; we can either normalize the proton dose for each pixel in the scan pattern [5] or we can employ rapid repeated scanning [4]. If the second method is used, more than 30 scans are typically needed. Repeated scanning is more suitable for sensitive resists such as SU-8 which require a much lower proton dose than the more conventional PMMA. In this paper the first proton beam micromachining exposures performed with the recently installed state of the art 3.5 MV HVEE Singletron™ particle accelerator are presented. The first exposures show that an even dose can be obtained with only a few scans over the sample. Proton beam micromachining with the new machine can routinely be performed with smaller beam spot sizes. To take advantage of the improved stability and resolution a new scanning system is being developed. The new system will utilise a National Instruments PCI-6111E Multi i/o card which has two 16 bits DACs and a minimum update time of 0.4 μs.

3. High-energy proton beam micromachining

Fig. 1a and b each show an array of four pillars with an area of $20\,\mu m \times 20\,\mu m$, manufactured using proton beams from the Van de Graaff accelerator. The structures are produced in 20 μm thick SU-8 layer on a Si wafer; the resist layer having been laid down using the spin coating technique. The thickness of the SU-8 layer was adjusted to

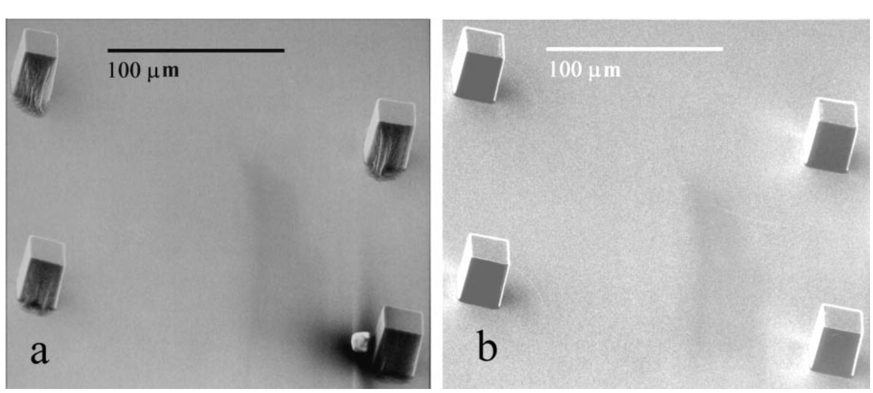

Fig. 1. SEM micrographs of pillars produced in a 20 μm SU-8 layer on a Si wafer. In (a) no beam blanking was employed and in (b) beam blanking was employed.

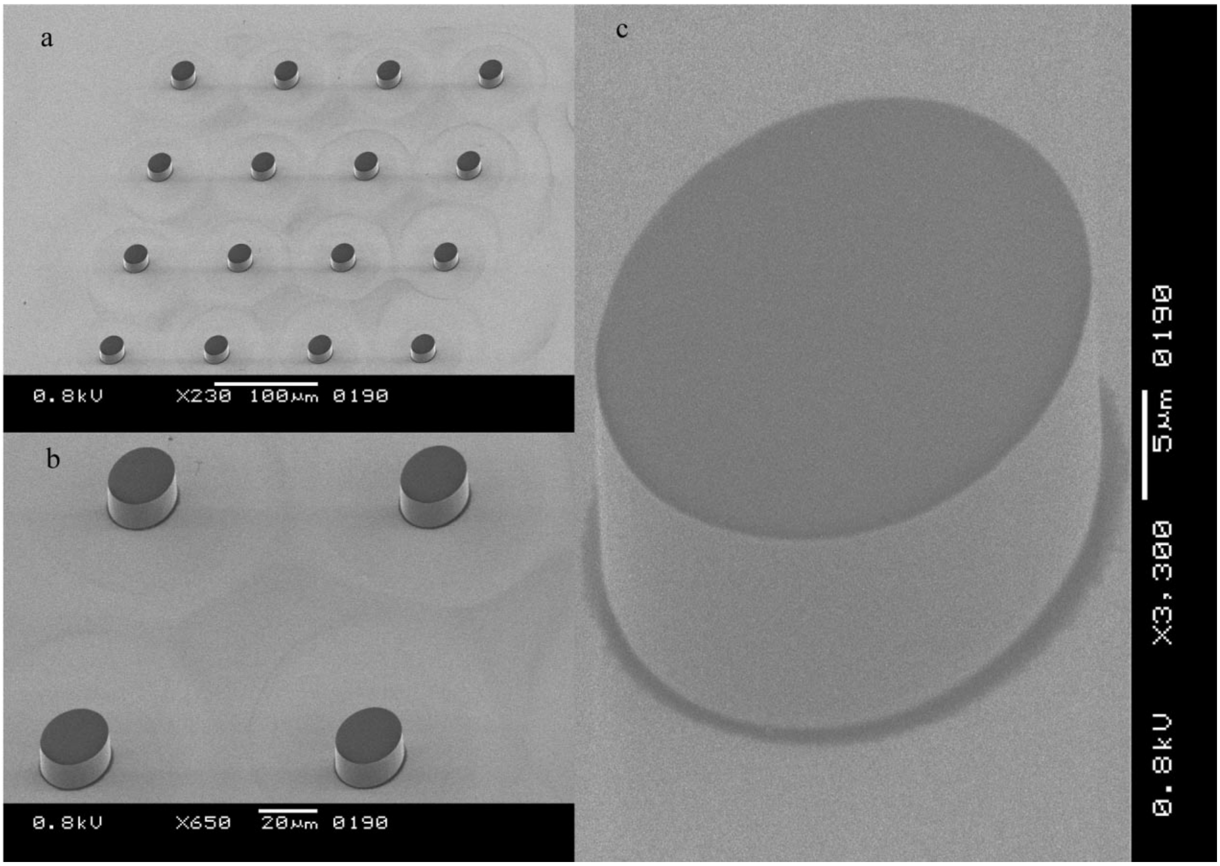

Fig. 2. SEM micrographs of a 4 × 4 matrix of circular pillars, each with a 20 µm diameter produced in a 20 µm SU-8 layer on a Si wafer.

20 µm to prevent the end of range broadening occurring in the resist layer. Because SU-8 is a negative resist, the structures that remain after development are those that have been subjected to proton exposure. The pillars in Fig. 1a are produced without beam blanking and the pillars in Fig. 1b with blanking. Fig. 1b is an example of microstructures with near 90° sidewalls (estimated at 89.5°).

Proton beam micromachining is not limited to rectangular structures. In Fig. 2 a set of cylindrical shapes are shown. These round pillars are exposed in sets of 16 with proton beam from the new HVEE Singletron™ particle accelerator; they have a diameter of 20 µm and are produced in a 20 µm thick SU-8 layer on a Si wafer. The exposure was performed in an area of 400 µm × 400 µm using a grid of 4096 × 4096 pixels. Fig. 2a shows the full area, Fig. 2b and c show close-ups of the structures. Another example is shown in Fig. 3, here a set of concentric circles is produced in a 20 µm thick SU-8 layer on Si. The exposure was performed in an area of 400 µm × 400 µm using a grid of 1024 × 1024 pixels, also employing the new accelerator. Comparing Figs. 2 and 3 it is clear that the edges in Fig. 2 are of higher quality because of the higher scan resolution used.

Fig. 4 shows a set of cantilevers and supported bridges. The structures are produced in a single layer of 36 µm SU-8 resist. The cantilevers have a length of 170 µm and the double supported bridges have a length of 80 µm, each finger has a width of 20 µm and a height of 22 µm. These structures are designed to measure the mechanical characteristics of SU-8 exposed using protons. To produce the structures shown in Fig. 4, two exposures were performed with 1 and 2 MeV protons using the van de Graaff accelerator.

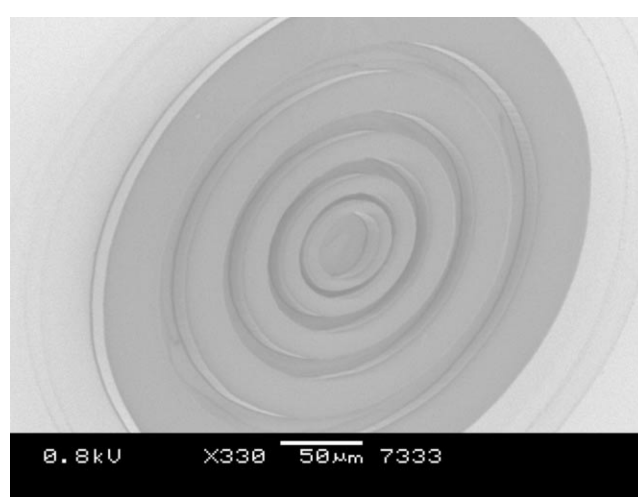

Fig. 3. SEM micrographs of concentric circles, produced in a 20 µm SU-8 layer on a Si wafer.

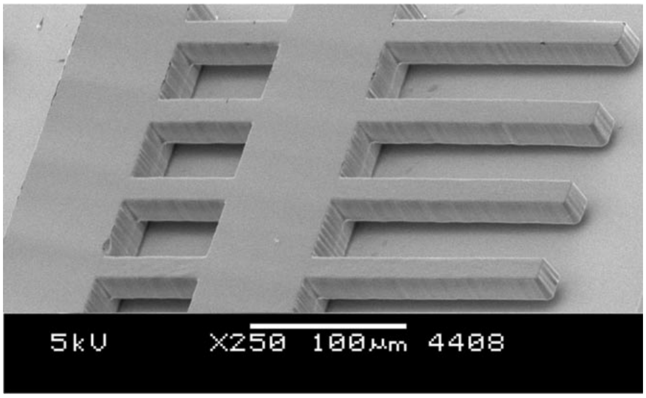

Fig. 4. Cantilevers produced in a 36 μm layer of SU-8 resist using two exposures at proton energies of 1 and 2 MeV.

The 1 MeV protons have a range of 22 μm in the SU-8 layer and therefore this exposure produced the double supported bridges and the cantilevers. The two supporting anchors, perpendicular to the first set, were exposed with 2 MeV protons. At 2 MeV, the protons penetrate through the whole SU-8 layer and are stopped in the supporting Si wafer. Alignment of multiple exposures is achieved by means of a marker on the resist layer, which is mapped using proton induced X-ray emission or backscattered proton signals [10].

4. Production of metallic structures using Ni plating

A crucial step in the development of mechanically strong microstructures for molds and stamps is the conversion of the mechanically weak structures made from resist material to metallic microstructures. An array of 81 (9 × 9) micro pillars was produced in 20 μm SU-8 on a Si wafer coated with Cu as a seed layer for plating. As in Fig. 1b the pillars are produced with the van de Graaff accelerator. The 81 micro pillars, each with dimensions of 20 μm × 20 μm were produced in an area 400 μm × 400 μm. After the development of the exposed SU-8, the sample was electroplated with Ni in a modified Watts bath [11]. The current density used was typically 50 mA/cm^2, corresponding to a plating rate of 1 μm/min, and the plated thickness adjusted to 10 μm. Directly after plating the remaining SU-8 was removed with SU-8 remover (nano remover PG™). In Fig. 5a–c, SEM micrographs of the Ni grids produced are shown, showing that the grids are well defined with smooth vertical walls. Because of the quality of these grids, we intend to use these

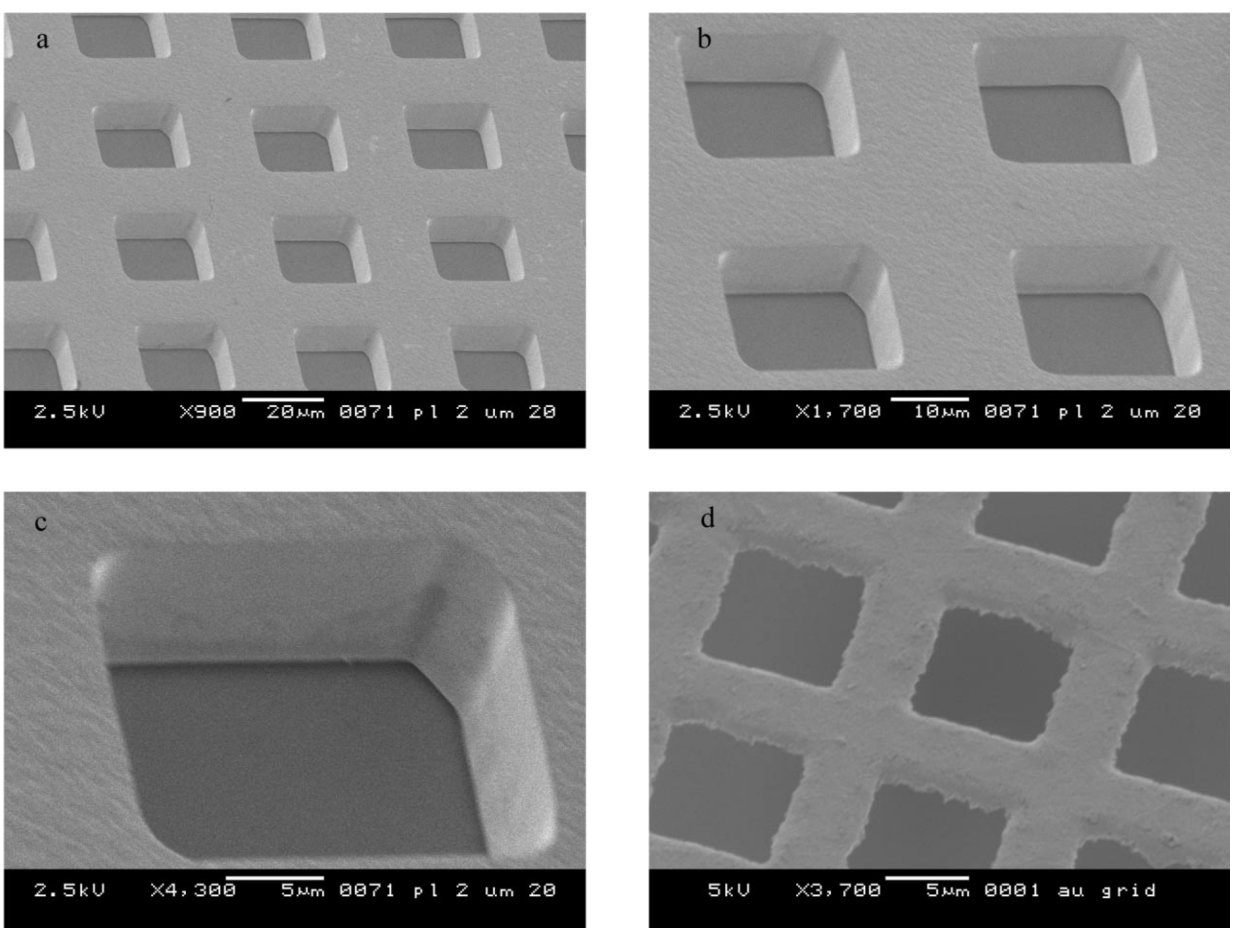

Fig. 5. (a–c) SEM micrographs of 10 μm thick PBM produced Ni plated grids are shown. (d) A standard 2000 mesh Au grid is shown for comparison.

grids as a new resolution standard for nuclear microscopy [12]. The resolution standard currently adopted by many nuclear microscopy groups worldwide is the electroplated 2000 lines per inch mesh gold grid (see Fig. 5d). This commercial 2000 mesh grid is much inferior in terms of edge definition and wall orthogonality compared with our Ni plated PBM grids.

5. Conclusions

In proton beam micromaching 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 in general slower than masked processes for bulk production, it is very suitable for rapid prototyping and the manufacture of molds and stamps. The introduction of a blanking system improved the quality of the direct write proton beam micromachined microstructures substantially.

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 addition, by changing the angle of the resist with respect to the beam, complex non-prismatic shapes can be machined with very well-defined sharp edges. With the new HVEE 3.5 MV accelerator, deep structures up to 160 μm can be produced with 3.5 MeV protons. The new machine, because of its increased beam brightness and high energy stability, opens the way to even more precise microstructures.

Proton beam micromachining has the potential to produce stamps and molds that can then be used repeatedly for batch and high-volume production. As demonstrated in this paper, microstructures produced in resist using PBM can successfully be electroplated to produce metallic components with high dimensional accuracy.

References

[1] F. Cerrina, in: P. Rai Choudury (Ed.), Handbook of Microlithography, Micromachining and Microfabrication, Vol. 1, Chapter 3, SPIE Press Monograph PM39, 1997, pp. 251–319.

[2] F. Watt, J.A. van Kan, T. Osipowicz, Three-Dimensional Micro-fabrication Using Maskless Irradiation with MeV Ion Beams: Proton-Beam Micromachining, MRS Bull., 2000, pp 33–38.

[3] J.A. van Kan, J.L. Sanchez, T. Osipowicz, F. Watt, Proton micromachining: a new technique for the production of three-dimensional microstructures, Microsyst. Technol. 6 (2000) 82–85.

[4] J.A. van Kan, J.L. Sanchez, B. Xu, T. Osipowicz, F. Watt, Micromachining using focused high energy ion beams: deep ion beam lithography, Nucl. Instr. Methods B148 (1999) 1085–1089.

[5] J.L. Sanchez, J.A. van Kan, T. Osipowicz, S.V. Springham, F. Watt, A high resolution beam scanning system for deep ion beam lithography, Nucl. Instr. Methods B136-138 (1998) 385–389.

[6] H. Lorenz, M. Despont, N. Fahrni, N. LaBianca, P. Renaud, P. Vettiger, SU-8: a low-cost negative resist for MEMS, J. Micromech. Microeng. 7 (1997) 121–124.

[7] F. Watt, I. Orlic, K.K. Loh, C.H. Sow, P. Thong, S.C. Liew, T. Osipowicz, T.F. Choo, S.M. Tang, The National University of Singapore nuclear microscope facility, Nucl. Instr. Methods B85 (1994) 708–715.

[8] F. Watt, T. Osipowicz, T.F. Choo, I. Orlic, S.M. Tang, Nuclear microprobe analysis and imaging: current state of the art performances, Nucl. Instr. Methods B136-138 (1998) 313–317.

[9] J.A. van Kan, J.L. Sanchez, B. Xu, T. Osipowicz, F. Watt, Resist material for proton micromachining, Nucl. Instr. Methods B158 (1999) 179–184.

[10] S.A.E. Johansson, J.L. Campbell, PIXE-A Novel Technique for Elemental Analysis, Wiley, 1988.

[11] F.A. Lowenheim Electroplating, McGraw-Hill, New York, 1978, pp. 212–216.

[12] F. Watt, T.F. Choo, K.K. Lee, T. Osipowicz, I. Orlic, S.M. Tang, The effect of external fields and slit scattering on the beam spot profile of the coupled triplet system, Nucl. Instr. Methods B104 (1995) 101–106.

Biographies

J.A. van Kan is a research fellow at the Department of Physics at the National University of Singapore. He received his PhD in experimental nuclear physics at the "Vrije Universiteit van Ansterdam" in 1996. His research interests are the use of high-energy proton beams for micromachining and the application of this process to micro-electro-mechanical systems (MEMS).

A.A. Bettiol is an NSTB fellow in the Department of Physics at the National University of Singapore. He received his PhD in experimental nuclear physics at the University of Melbourne, Australia in 2000. His main research interests are the interaction of energetic ion beams with materials and micromachining.

B.S. Wee is a graduate student at the National University of Singapore.

T.C. Sum is a graduate student at the National University of Singapore.

S.M. Tang is a professor of physics at the National University of Singapore. He received his PhD in experimental nuclear physics from Indiana University in 1966. His current main research interests are the application of ion-beam techniques for aerosols studies.

F. Watt is a professor of physics at the National University of Singapore. He received his PhD in experimental physics from the University of Newcastle, England in 1971. His current research interests are the use of applied nuclear-particle-beam techniques in interdisciplinary research, with special emphasis on elemental analysis in biomedical research.