Micromachining using a focused MeV proton beam for the production of high precision 3D microstructures with vertical sidewalls of high orthogonality

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ABSTRACT

The production of high aspect ratio microstructures requires a lithographic technique capable of producing microstructures with vertical sidewalls. There are few techniques (eg proton beam micromachining, LIGA and Stereolithoghaphy) capable of producing high aspect ratio microstructures at sub-micron dimensions. In Proton Beam Micromachining (PBM), a high energy (eg 2 MeV) proton beam is focused to a sub-micron spot size and scanned over a resist material (eg 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. These features enable the production of multilevel microstructures with vertical sidewalls of high orthogonality. Proton beam micromachining is a fast direct write lithographic technique; in a few seconds a complicated pattern in an area of 400 x 400 μm^2 can be exposed down to a depth of 150 μm. These features make proton beam micromachining a technique of high potential for the production of high-aspect-ratio-structures at a much lower total cost than the LIGA process, which requires a synchrotron radiation source and precision masks.
Research is currently under way to improve the process that employs the SU-8 negative photo-resist as a mold to electroplate Ni. Experiments have shown that post-bake and curing steps are not required in this SU-8 process, reducing the effects of cracking and internal stress in the resist. Plated Ni structures can be easily produced which are high quality negative copies of the SU-8 produced microstructures.

Keywords: Micromachining, high aspect ratio, nuclear microscope, proton beam, electroplating, 3D microstructures.

1. INTRODUCTION

Most of the existing methods in the semiconductor industry of making microelectronic components are essentially 2D. As semiconductor devices are scaled down in size there is a rising demand for smaller MEMS devices and integration of moving parts on a chip. High aspect ratio 3D microstructures with sub-micron details are also of growing interest for optoelectronic devices. It is therefore essential to develop new lithographic techniques suitable for the production of thick three-dimensional microcomponents. One of the more established techniques for 3D micromachining is LIGA[1], one setback is the relative high production cost involved. There are a few emerging new lithoraphies (e.g. PBM, DUV lithography and stereo micolithography). Proton Beam Micromachining (PBM) is being developed at the Research Centre for Nuclear Microscopy (RCNM) and has shown to be a promising new 3D lithographic technique. In PBM a focused beam of MeV protons is used to produce a 3D latent image in a resist material[2,3]. Of these new techniques PBM is the only technique that offers the capability of direct write sub-micron sized high aspect ratio microstructures.
Recent developments of PBM will be discussed in this paper. These developments include hardware and software improvements as well as novel processing steps. First PBM tests with the newly installed high performance HVEE 3.5 MV particle accelerator (Singletron) are discussed. A new scanning system based on a user friendly and highly automated Lab VIEW™ environment has made PBM more flexible. This system is capable of scanning over an area up to 2 x 2 mm^2, maintaining sub micrometer pixel resolution. A multilevel circuit for fluidic applications has been designed and fabricated in SU-8. The fluidic circuit was produced in one single layer of SU-8 resist and consists of a covered complicated micro-channel circuit and a concealed reservoir. A crucial step in the development of mechanically strong microstructures is the conversion of structures made from resist material of low hardness and strength, to harder and more durable metallic microstructures. The implementation of a post lithographic process step such as electroplating offers the possibility of

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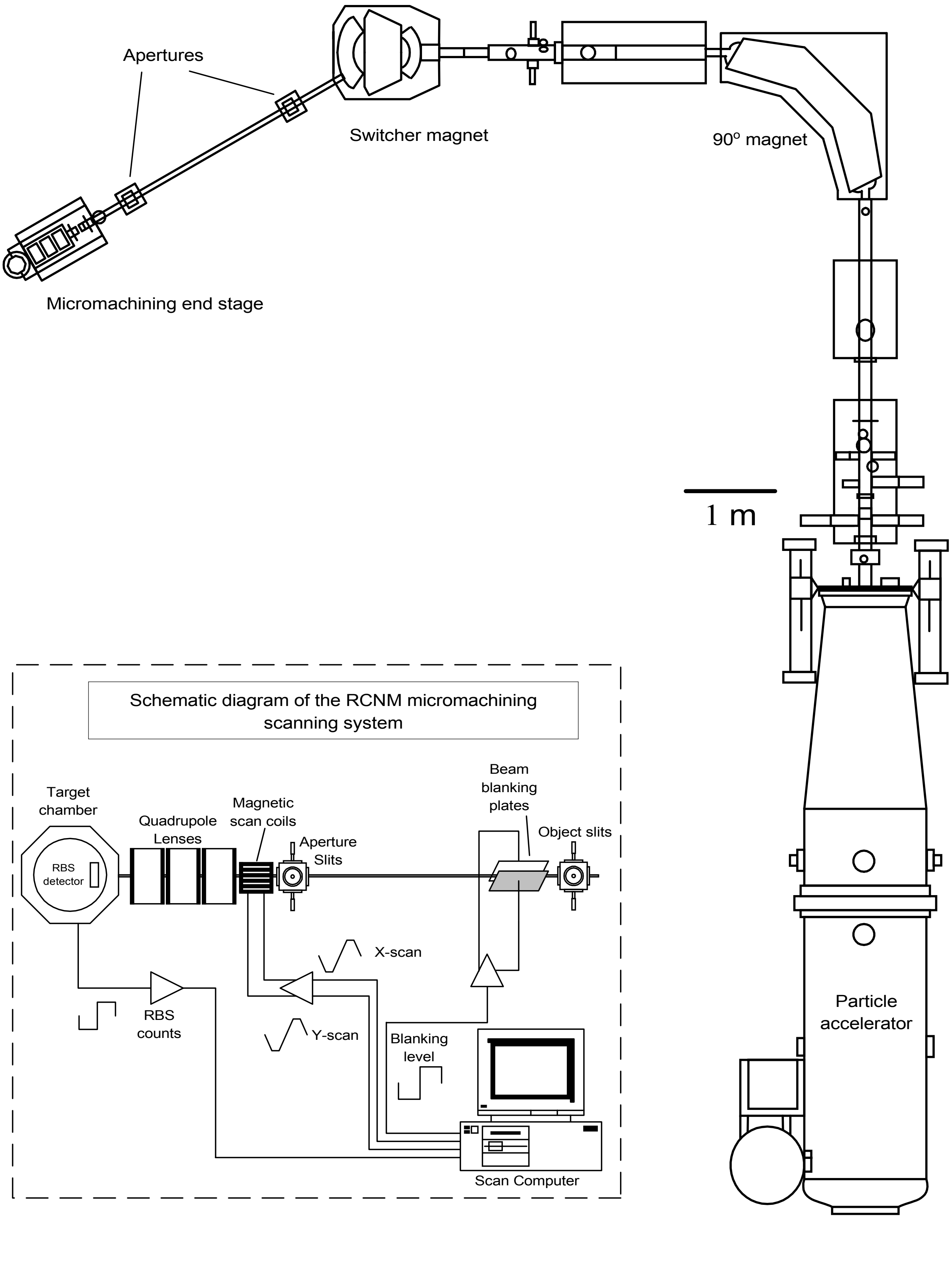

Figure 1 Proton Beam Micromachining set-up.

producing metallic structures. These PBM produced metallic microstructures can be used for batch and high volume production.

2. PHYSICAL CHARACTERISTICS OF PROTON BEAM MICROMACHINING

In PBM the path of a high energy proton in material is dependent on the interaction with the electrons and nuclei in the material. The probability that a proton interacts with an electron is a few orders of magnitude lager than for nuclear scattering in the first 50 % of its trajectory. Therefore only proton-electron interactions will be discussed. Proton-electron interactions hardly change the trajectory of a proton because of the mass ratio (m_p/m_e ~1800). This implies that the path of a proton hardly deviates from a straight line. Since the energy transfer in these collisions in rather small, with a peak around 100 eV, many collisions will occur before a proton comes to rest. Proton trajectories can be accurately simulated by means of Monte Carlo calculations for example using the computer code TRIM[4]. These features make PBM a predictable and an extremely powerful lithographic technique with the following key features:

Protons have a relatively large and well defined range in resist materials. For example by choosing a proton energy of 1.0 MeV or 3.5 MeV, structures with an exact height of 20 and 160 µm respectively can be produced. This allows the production of slots, holes and buried microchannels, tilting the sample allows even the production of non parallel microstructures. The small angle scattering allows the production of high aspect ratio structures. Calculations[5] have shown that a 3.5 MeV proton beam will spread less than 100 nm in a 10 µm thick layer of resist. Finally the relatively constant energy deposition along the proton track ensures uniform exposure rates along the path of the proton beam, again a requirement for the production of high quality sub-micron sized high aspect ratio microstructures.

3. DESCRIPTION OF PROTOTYPE HARDWARE SET-UP

A schematic overview of the proton beam micromachining facility used at the research Centre for Nuclear Microscopy (RCNM), National University of Singapore is shown in figure 1. Protons from a nuclear accelerator are focused down to sub-micron spot sizes and are used to direct write patterns in resist materials. Recently the PBM has been improved substantially with the introduction of a state of the art, high brightness, 3.5 MV single-ended accelerator (HVEE Singletron). This new machine produces proton beams of much higher stability than the belt driven Van de Graaff accelerator previously used for micromachining purposes.

The protons from the accelerator are energy analyzed using the 90º magnet. With the switcher magnet the protons are steered into the 30º nuclear microscope beam line, currently being used for the development of proton beam micromachining. In the inset of figure 1 we see a schematic diagram of the RCNM micromachining scanning system. The beam is focused down to sub-micron dimensions in the target chamber with a set of quadupole lenses and then used for lithography. This target chamber was designed for nuclear microscopy and thus not optimized for PBM. In the near future micromachining will be made more accessible and more accurate when a new chamber specially designed for PBM will be installed at the 10º line after the switcher magnet.

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. 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. The switching time for blanking is typically less than 1 µs. A typical exposure rate for SU-8 in the current system is about 1500 s/mm^2. In an optimized set-up, at state of the art proton current densities of 1 nA/µm^2, 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. The recently upgraded scan system utilizes a National Instruments PCI-6111E Multi i/o card which has two 16 bits DACs and a minimum update time of 0.4 µs. A typical exposure is performed in an area of 400 x 400 µm^2. With the upgraded scan system areas up to 2 x 2 mm^2 can be irradiated.

To guarantee a constant proton dose per pixel as the beam is digitally scanned across the resist, we developed two main methods for dose normalization. Both methods rely on the detection of Rutherford Backscattering Signals (RBS). In the first method the beam is moved to a new position in a scan after a fixed number of protons has been detected (pixel normalization). In the second method the beam is scanned rapidly over a figure for many times until a sufficient dose has been reached (figure scanning). In both cases the average dose per area can be chosen in the scanning program.

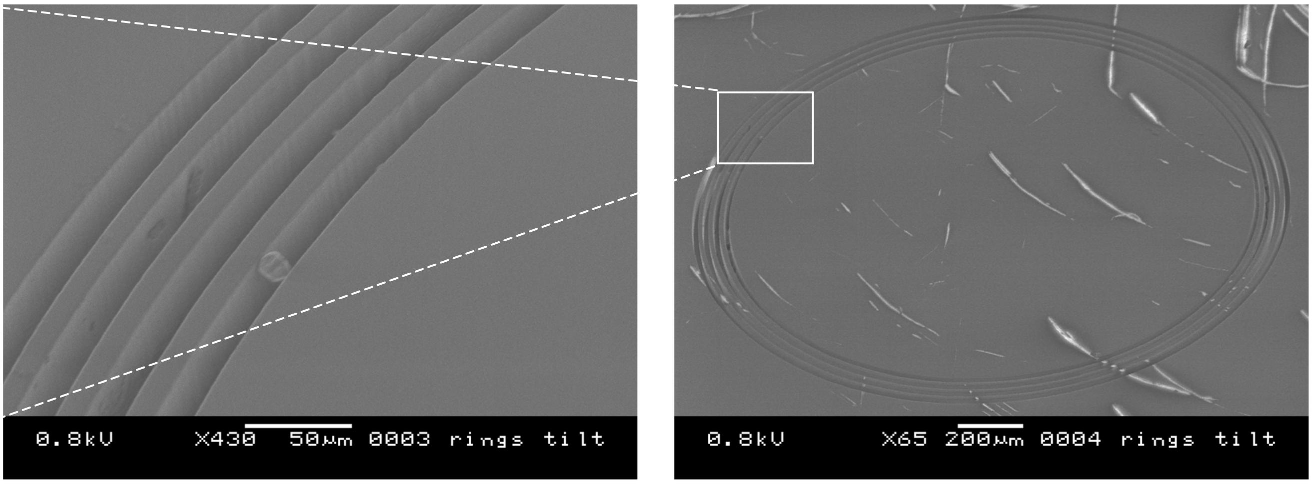

Figure 2 SEM micrograph of circular rings produced in thick PMMA.

4. RESIST PROCESSING

Five types of commercially available resist materials were tested[6] for PBM. The positive resists PMMA, AZP4620, AZ 9000 and PMGI; and the negative resist SU-8. The AZP4620 and AZ 9000 proved unsatisfactory. Both these resists show similar behavior, the irradiation with protons give rise to a combination of both cross-linking and chain-scissioning. PMGI needs a fairly high dose of 300 nC/mm^2 and the imaging qualities are not as good as the more preferred positive resist PMMA. 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. PMGI could in future experiments be used as buffer layer or sacrificial layer.

The SU-8 microstructures in this paper are all produced in “thin resist” (20 – 40 µm) layers. These resist layers were applied on Si wafers using the spin coating technique. First the Si wafers are baked to remove moisture at the surface. The resist is then applied on the wafer and spun for typically 100 s at 1000 rpm; the exact conditions are dependent upon the resist type and desired thickness of the resist layer. Finally the sample is baked at about 95ºC to harden the resist layer and to reduce stress.

After exposure the samples are developed in a chemical solution. The type of developer depends on the resist used, and the development time is a function of the thickness of the resist layer, the complexity of the structure, the proton dose used and the temperature. The PMMA layers were developed using the procedure given elsewhere[7]. The other resists (AZ P4620, AZ 9000, PMGI SF 23 and SU-8) were developed at room temperature using a common developer supplied by the manufacturers of the resists. Typical development times for these three resists are 3 to 7 minutes. In case of SU-8 processing this treatment provides sufficient cross-linking and the structures are ready for mechanical testing or plating: no post bake or curing is needed.

5. PBM FABRICATED RESIST STRUCTURES

In figure 2 an example of concentric rings with a diameter of 2 mm and a width of 20 µm is shown. The rings are exposed using a proton energy of 2 MeV in a thick piece of PMMA. The protons have a penetration depth of 62 µm, which corresponds to the depth of the resulting machined structures. The resolution used for writing the circles is 1 µm/pixel. From the highest magnification (left) it is clear that micron sized features can be produced in mm sized structures.

Figure 3 shows an optical micrograph of a fluidic circuit which consists out of four sets of buried micro-channels and three reservoirs encompassing a total area of 2 x 4 mm^2. The whole structures is produced in one single layer of 36 µm thick SU-8. This type of multi-layered structures are produced using multiple exposures at different proton energies. Two exposures were carried out with 0.5 and 2 MeV protons. The dark regions (eg the whole area except the micro-channels and the reservoirs) were exposed using 2 MeV protons, which penetrate though the SU-8 layer into the substrate. Note that the exposed areas become insoluble for the developer. The 0.5 MeV protons have a range of 5.0 µm and therefore the 0.5 MeV

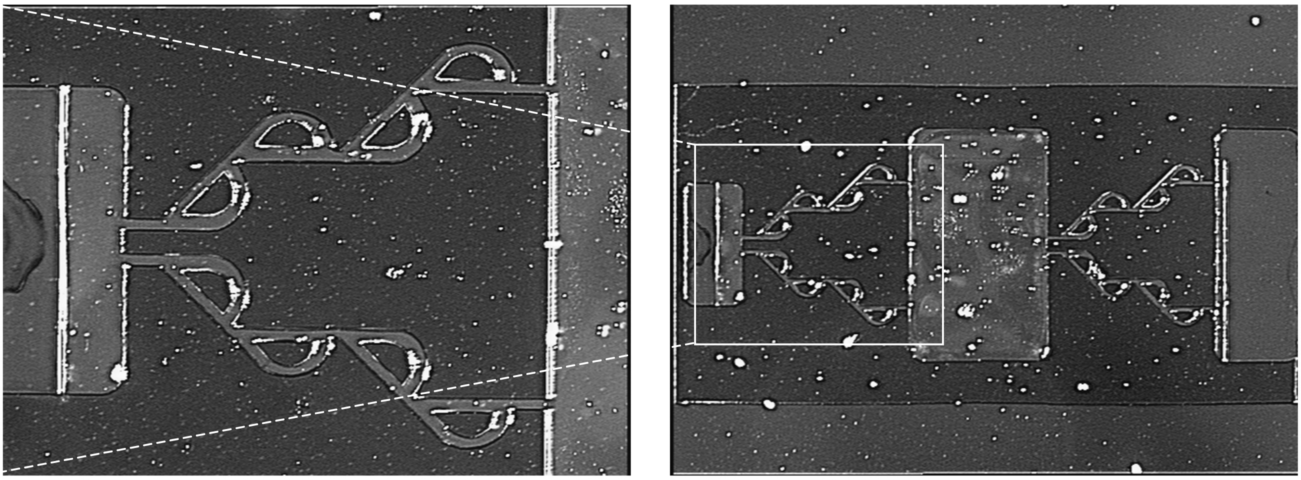

Figure 3 Optical image of a fluid circuit (2 x 4 mm^2) micro-machined in one single layer of SU-8

protons were used to cover the micro-channels, the centre reservoir and a small part of the other two reservoirs. In this way the centre reservoir is only connected to the outside via the four sets of micro-channels. The buried micro-channels have a width of 40 μm and a height of 30 μm.

In another example two different sets of square pillars were proton beam machined in a 20 μm thick SU-8 layer using 2 MeV protons. The SU-8 layer was spin-coated on to a Si wafer which had been previously coated with a thin conducting Cu layer to act as a seed layer for plating. The width of each of the first set of square pillars is 7.5 μm, exposed in an area of 200 x 200 μm^2. A separate set with a width of 15 μm was produced in an area of 400 x 400 μm^2. The left part of figure 4 shows an SEM micrograph with high magnification of the smallest set of pillars. From the SEM micrograph the sidewalls can be estimated to project an angle of 89.5^o to the silicon surface, which is near vertical. In the right part of figure 4 a lower magnification image is shown for the pillars with a width of 15 μm.

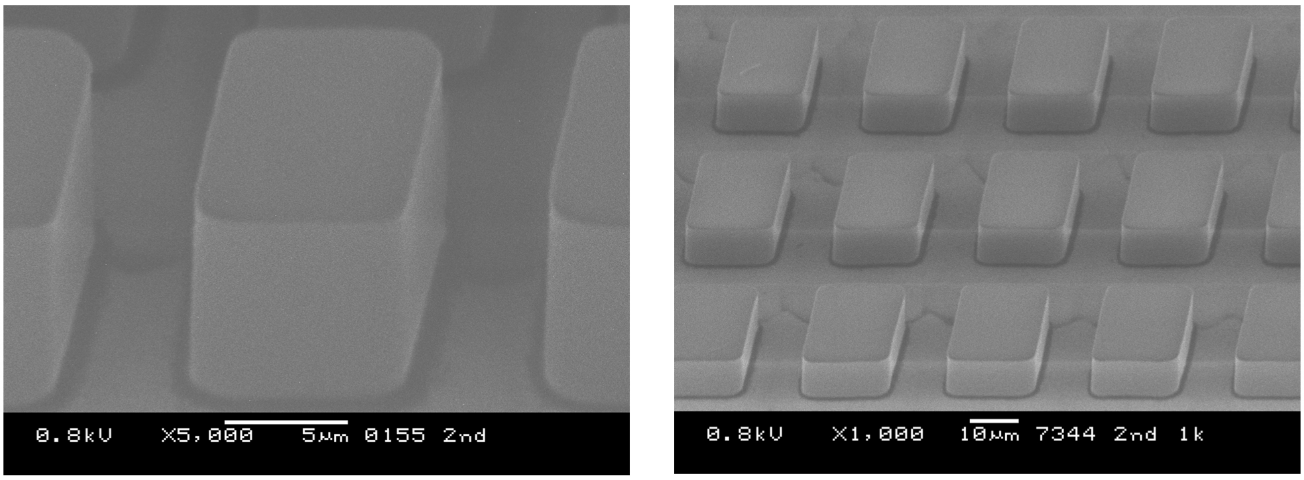

Figure 4 SEM micrographs of pillars produced in 20 μm thick SU-8 on a Si wafer.
The pillars have a size of 7.5 x 7.5 μm^2 (left) and 15 x 15 μm^2 (right).

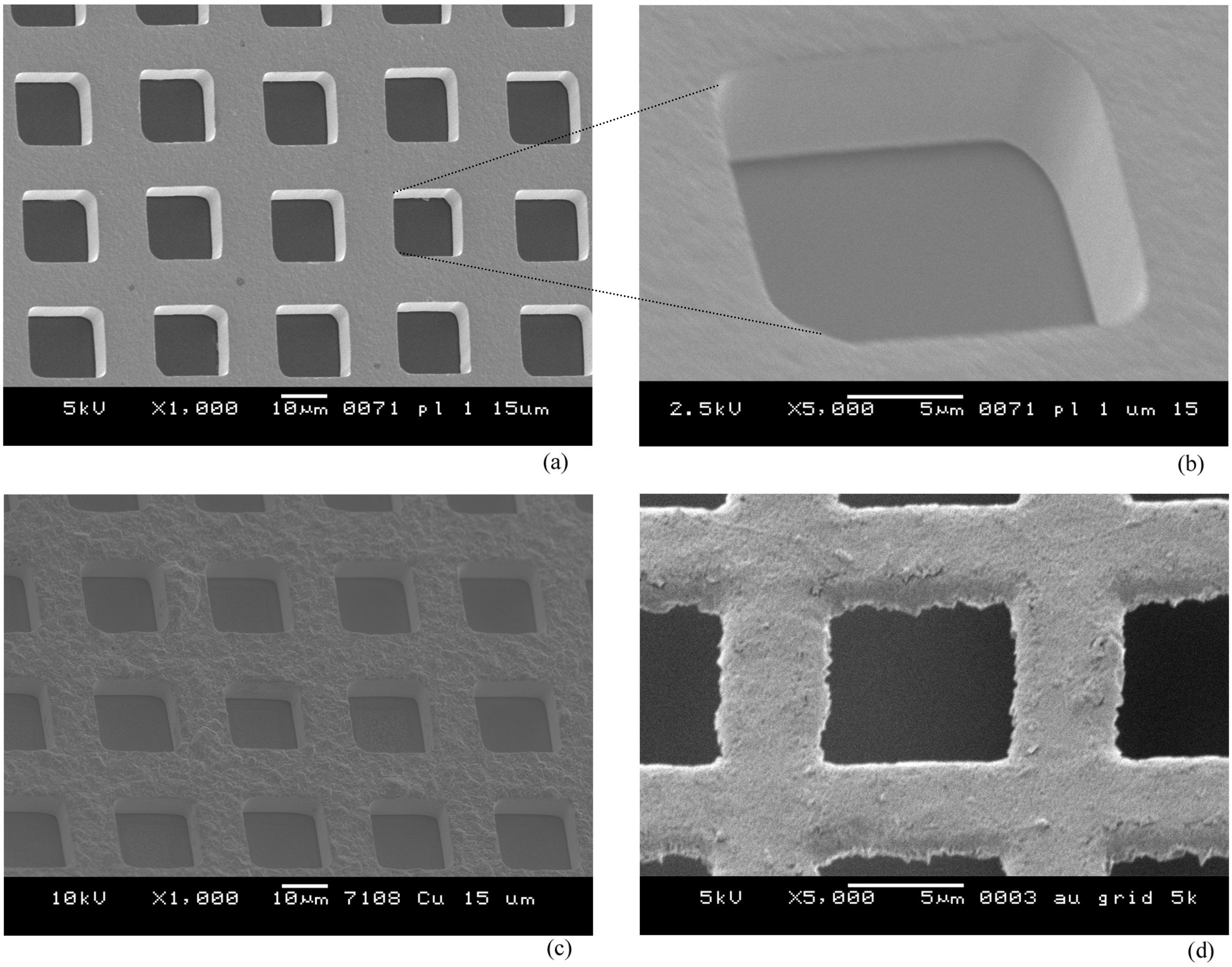

Figure 5 SEM micrographs of electroplated Ni (a and b) and Cu (c) grids produced using PBM.
The holes and spaces are 15 µm. In (d) a commercially available 2000 mesh Au grid is shown.

6. ELECTROPLATING

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 micro pillars was produced in a 20 µm SU-8 on a Si wafer coated with Cu as a seed layer for plating. The conversion to metallic structures has been performed with two different types of electro plating baths. For Cu plating a standard Copper Sulfate bath was used whereas the Ni was produced using a modified Watts bath[8].

After development, the areas between the SU-8 pillars were electroplated. The SU-8 was subsequently removed with SU-8 remover (nano remover PG™). In figure 5 the Ni (a and b) and Cu (c) plated structures (i.e. the negative of the pillars) are shown. Typical plating currents for Ni and Cu are 50 mA/cm^2 and 30 mA/cm^2 respectively, the plated thickness was adjusted to an arbitrary thickness of 10 µm. Both Ni and Cu plating show high degree of sidewall smoothness with vertical sidewalls. The roughness of the Cu surface is most likely due to high plating rate and is being under further investigation. In figure 5 (b) a high magnification micrograph of the Ni grid with 15 µm holes and ridges is shown. As comparison, a standard 2000 mesh lines per inch gold mesh used as a resolution standard in nuclear microscopy is shown in figure 5 (d). Figures 5 (b) and (d) are shown with the same magnification for direct comparison.

Because of the quality of PBM electroplated grids, we intend to use these grids as a new resolution standard for nuclear microscopy[9]. The commercial 2000 mesh grid shown in figure 5 (d) is much inferior in terms of edge definition and wall orthogonality compared with our Ni plated PBM grids.

7. 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 the new HVEE 3.5 MV accelerator improved the quality of the direct write proton beam micromachined microstructures substantially. Combined with a new scanning system, proton beam micromachining is able to produce large structures (mm sized) with details down to the micrometer level. Note that the exposures were done in a target chamber which was designed for nuclear microscopy and not for proton beam micromachining. Therefore the current results have space for improvement. A newly designed proton beam micromachining chamber will improve the quality of the produced microstructures.

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 shapes can be machined with very well defined sharp edges. As shown this can be used for fluidic applications. 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.

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