IMPROVEMENT IN PROTON BEAM WRITING AT THE NANO SCALE

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ABSTRACT

Here we report on the progress of 3D nano machining using MeV protons. In proton beam (p-beam) writing a proton beam is typically focused down to a sub 100 nm spot size and scanned over a resist material (e.g. Su-8 or PMMA). Currently the scanning is performed using a magnetic scan coil which has an intrinsically long settling time. A new scanning system is introduced which employs electrostatic scanning and allows an increase in writing speed up to 2 orders of magnitude.

1. INTRODUCTION

Current microelectronics production technologies are essentially two-dimensional (2D), well suited for the 2D topologies prevalent in microelectronics. As semiconductor devices are scaled down in size coupled with the integration of moving parts on a chip there will be a rising demand for smaller Micro Electro Mechanical System (MEMS) devices. High aspect ratio three-dimensional (3D) microstructures with sub-micron details are also of growing interest for optoelectronic devices, micro/nano-fluidics and nano-imprinting. Although electron beam (e-beam) writing is utilised effectively in many sub-100 nm applications, it is intrinsically difficult to produce sub-micron structures of high-aspect-ratio because electrons scatter as they penetrate the resist. Therefore it is essential to develop new lithographic techniques suitable for the production of high aspect ratio 3D micro- and nano-components. P-beam writing is being developed at the Centre for Ion Beam Applications (CIBA) and has shown to be a powerful new 3D lithographic technique [1-4]. The production of high aspect ratio microstructures requires a lithographic technique capable of producing microstructures with vertical sidewalls. When a MeV proton beam interacts with matter it follows an almost straight path, the depth of which is dependent on the proton beam energy. In p-beam writing the range of the induced secondary electrons is limited to a few nm [1,5] because of the high mass ratio between proton and electron. These features enable the production of nanometer sized polymer structures. P-beam writing is therefore a powerful new technique that offers the capability of direct write high aspect ratio nano- and microstructures.

2. EXPERIMENTAL SET-UP

A new nuclear nanoprobe facility has been developed at the CIBA [1], see figure 1. This facility is the first of its kind dedicated to p-beam writing on a micron as well as on a nano scale. The p-beam writer utilizes the Oxford Microbeams high demagnification lenses (OM52) in a high excitation triplet configuration. This lens system operates at an object distance of 7 m and a reduced image distance of 70 mm resulting in enhanced system demagnifications (228 x 60 in the X and Y directions respectively).

The sample is mounted on a computer controlled Burleigh Inchworm XYZ stage which has a travel of 25 mm for all axes with a 20 nm closed loop resolution. The system has been designed to be compatible with Si wafers up to 6". This new focusing system is able to produce proton beams down to a sub-100 nm spot size, which can be used for mask less direct write lithography.

During exposures the beam is scanned over the resist in a digitized pattern using a set of electromagnetic scan coils, located directly in front of the quadrupole lens system. In this way scan fields up to 1 x 1 mm^2 can be achieved. To prevent deposition in the sample of any unwanted dose we use 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. The scan system utilizes a National Instruments NI 6731 Multi i/o card which has four 16 bit
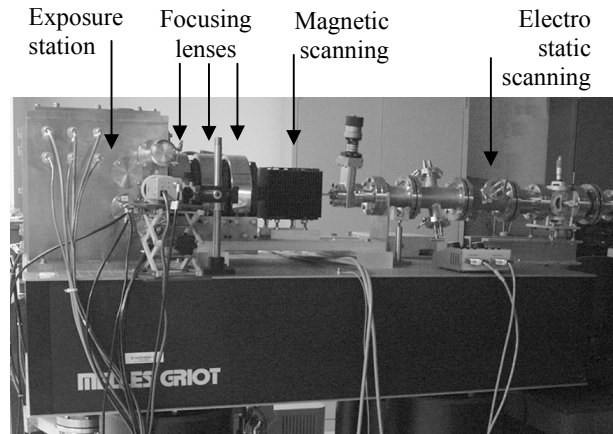
Figure 1: P-beam writing end station set-up. In the exposure station wafers up to 6" can be exposed.

digital to analog converters (DACs) and has a minimum update time of 1.0 μs. Two channels control the scan coils and a third DAC controls the beam deflection. This improved resolution is necessary to cope with the reduced beam spot size available in the new dedicated proton beam micromachining beam line. The scan software supports AUTOCAD and Bitmap file format; more details about the scanning system can be found elsewhere [6].

Since magnetic scanning systems have a relatively long settling time due to the magnetic scan coils resulting in a relative slow writing speed, we introduce here a faster electrostatic scanning system to allow us to reduce exposure times. For the electrostatic scanning we have evaluated 2 power supplies, the first one is a Fischer dual +/- 220 V High Voltage Amplifier with a slew rate of up to 1000 V/μs and the second is a Trek 609E-6 +/- 4 kV High-Voltage Amplifier with a slew rate of more than 150 V/μs.

Because of the high demagnification the p-beam writing system can have only one pre-lens scanning system with large area (currently magnetic scanning up to 1x1 mm^2) which has to be located directly in front of the lenses. The new electrostatic scanning is therefore currently limited to an area of 50 x 50 μm^2. An alternative way of writing structures can be performed using stage scanning which allows the beam to be scanned over the full 25 x 25 mm^2 range of the XYZ stage.

3. RESULTS

3D-Structures

Figure 2 shows a scanning electron micrograph (SEM) of 2 x 2 μm^2 Su-8 pillars (10 μm high) which are written on a UV cured layer of Su-8. Su-8 is a negative tone resist under p-beam exposure. The pillars were written in a matrix of 2048 x 2048 pixels, using a 2 MeV proton beam which was focused down to 200 x 200 nm^2. A special algorithm was employed to reduce the effects of long settling times in magnetic scanning. Every pillar was written using a spiral scanning algorithm; many lines were written in a square shape with increased size to form a single pillar. Before
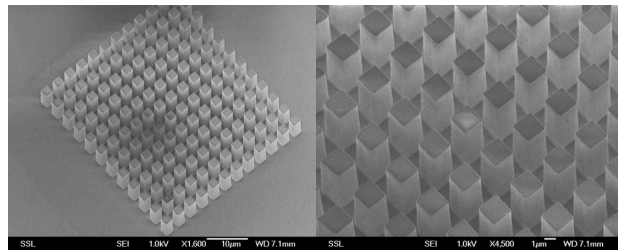

Figure 2: SEM image of 2 x 2 μm^2 pillars in a 10 μm thick Su-8 layer which was applied on a UV cured Su-8 layer. These structures were written with a focused 2 MeV proton beam using magnetic scanning using a pixel dwell time of 250 μs.

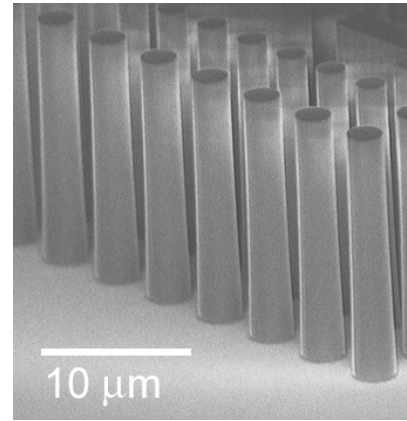Figure 3. SEM image of circular pillars of 2 and 1.5 μm diameter, written in a 20 μm thick Su-8 layer which was applied on a Si wafer. These structures were written with a focused 2 MeV proton beam.

moving to the next pillar the beam was brought back to the centre and blanked before writing the next pillar. Here the dwell time per pixel had to be at least 250 μs in order to write rectangular pillars.

Besides simple squares more complex shapes can be written. Figure 3 shows circular pillars with the same smoothness as the square pillars discussed earlier. They are written in a 20 μm thick Su-8 layer applied on a Cu coated Si wafer written with a 2 MeV proton beam (180 x 180 nm^2). This figure was produce using a spiral scanning algorithm, both the pixel size and pixel dwell time were the same as in figure 2. The smallest pillars have an aspect ratio of more than 10. The substrate here is metallic compared to a polymer in figure 2 which shows that in p-beam writing the type of substrate does not affect the quality of the written structures.

Electrostatic scanning

To compare the new electrostatic scanning system with the conventional magnetic scanning system sets of pillars similar to the ones in figure 2 were written in a 10 μm thick Su-8 layer applied on a Au coated Si wafer. In order to see the problem with fast magnetic scanning the edges of the pillars were separately written in a raster scanning mode. In these tests we employed a 2 MeV proton beam focused down to 250 x 250 nm^2. The scanning was performed using a pixel dwell time between 6.4 and 17 μs per pixel. As can be seen in figure 3 (top) the pillars written using the magnetic scanning have irregular shapes. This can be explained as follows, while raster scanning the edges the beam position is not accurately known due to the long settling times of the magnetic field and therefore the blanking is not properly synchronized. Writing the same pattern using electrostatic scanning (Fischer power supply) produces rectangular squares using a 16.9 μs pixel dwell time, as can be seen in figure 3 (right bottom). The pillars written with a pixel dwell
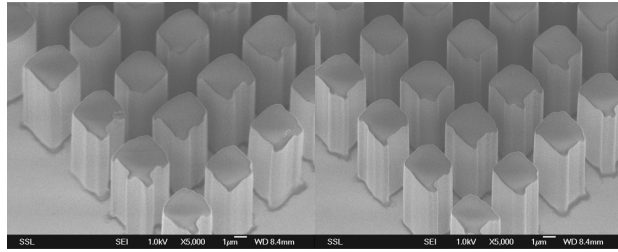
Magnetic scanning
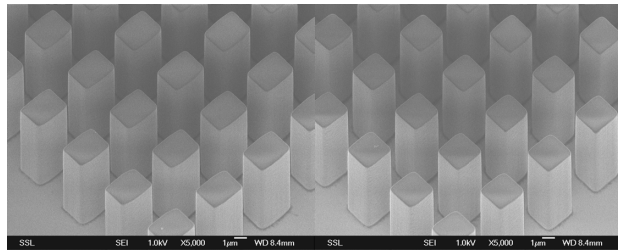
Electrostatic scanning

Figure 3: SEM image of 2 x 2 μm² pillars in a 10 μm thick Su-8 layer on Si. These structures were written with a focused 2 MeV proton beam (250 x 250 nm²). The top part uses magnetic scanning with a pixel dwell time of 7.0 μs left and 16.9 μs right. Bottom is written using electrostatic scanning (Fischer power supply) with a pixel dwell time of 6.4 μs left and 16.9 μs right.

time of 6.4 μs per pixel are a bit elongated (figure 3 left bottom), this is probably caused by the response time of the electrostatic power supply resulting in a timing mismatch between the scanning and the blanking. The structures written with the Trek power supply are almost as well defined as the ones shown in figure 3 (bottom), they are a bit wider because of the slower slew rate.

The electrostatic scanning system, currently limited to a scan size of 50 x 50 μm² can be upgraded to reach a similar size as the current magnetic system (1 x 1 mm²). In an adjusted set-up we plan to replace the magnetic scanning with electrostatic scanning to make p-beam writing faster over a lager area. An other alternative would be to stitch several fields written using electrostatic scanning combined with stage scanning.

Nanolithography

In the final examples we demonstrate the nano lithographic capabilities of p-beam writing. Parallel grooves and lines were written within a 20 x 20 μm² area in a 350 nm thick PMMA film spincoated on Si, PMMA is a positive resist under p-beam writitng. Since imaging of sub 100 nm structures in polymer films requires special sample preparation, these structures were written parallel with the edge of the sample and 30 μm from the edge. Using a precision diamond scriber/breaker we cleaved the Si along a crystal plane which encompassed the line structures, allowing us to image the cross sectional profile. The high
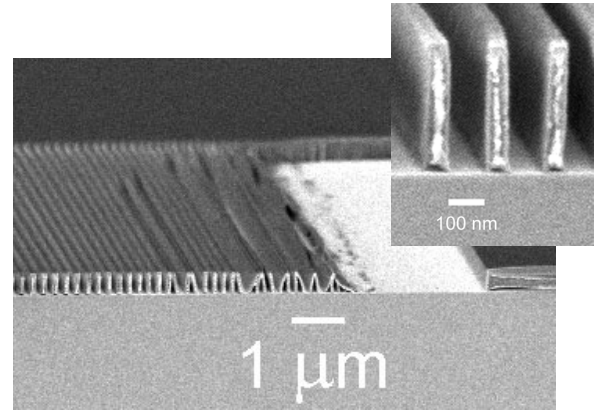

Figure 5: SEM image of parallel lines written in a 350 nm thick PMMA layer. The structure was written with a focused 2 MeV proton beam. The inset indicates a wall width of 50 nm.

aspect ratio walls, estimated to be 50 nm wide, are shown in figure 5.

From left to right the width of the lines is reduced gradually. The width of the lines is stepped down by 10 nm after a group of 4 lines. This means that the narrowest lines must be 20 to 30 nm in width, they didn't survive the development and breaking process. New experiments are planned to further investigate the resolution limits of p-beam writing.

To determine the potential of p-beam writing in obtaining high aspect ratio, test structures were written using a 2 MeV
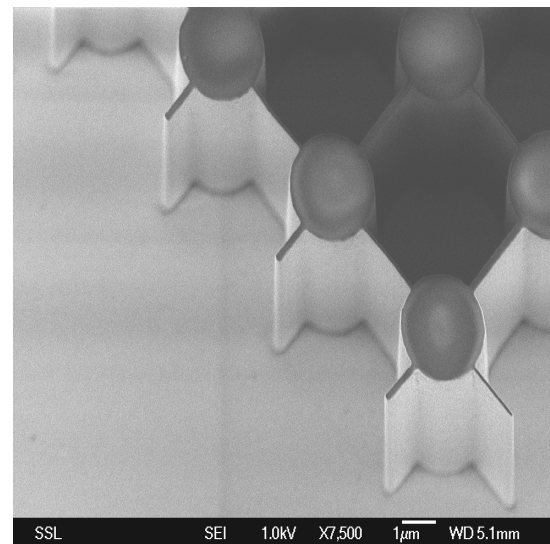

Figure 6. SEM image of 2 μm diameter circular pillars written in a 10 μm thick Su-8 layer. Linking the cylinders are high aspect ratio walls of width 60 and 120 nm. The structures were written with a 2 MeV proton beam.

proton beam in a 10 μm thick layer of Su-8, spin-coated onto a Si wafer. In this experiment 2 MeV protons were focussed down to a spot size of 60 x 120 nm^2 and scanned in a matrix of circular pillars (figure 6). During the exposure, extra lines were written through the centre of the cylinders forming a high aspect ratio nano grid. As can be seen in the SEM pictures in figure 6, the single written lines are 60 and 120 nm in width, which we believe is currently the smallest written single line in Su-8 [7]. The support given by the adjacent cylindrical pillars ensures that the structural integrity of the narrow walls is not degraded during the development procedures. The narrow wall structure exhibits an aspect ratio of more than 160. Only Bogdanov and Peredkov [7] have reported similar aspect ratios for Su-8 structures, but with a structural width of 4 μm or more.

4. CONCLUSIONS

Here we discussed the successful introduction of a new electrostatic scanning system which enables p-beam writing to be performed more accurately and faster avoiding the long settling times needed in the current magnetic scanning system. In these first test it has been demonstrated that the writing speed can be increased by a factor of 15. This is a first result; tests have to be performed to improve the electrostatic writing speed. Currently the scan area of the new electrostatic scan system is limited to 50 x 50 μm^2. Design studies are planned to upgrade this to 1 x 1 mm^2.

Although p-beam writing is in general slower than masked processes for bulk production, it is very suitable for rapid prototyping and in particular the manufacture of molds and stamps that can be used for batch and high-volume production using either nano imprinting or flash imprint lithography.

In the newly developed p-beam writing system a proton beam can be focused down to 35 x 75 nm^2 and directly scanned across a resist, thereby eliminating the need for a mask. This resolution is currently the best performance in the world for MeV protons [8]. Arbitrary shapes can be fabricated, high-aspect-ratios (more than 100) can be achieved in PMMA and Su-8 resist. The improved p-beam writing system has opened the way to even more precise micro- and nano-structures.

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