

PROTON BEAM NANO-MACHINING: A NEW 3D NANO LITHOGRAPHIC TECHNIQUE

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Abstract

A new nuclear nanoprobe facility has been developed at the Research Centre for Nuclear Microscopy in the Physics Department of the National University of Singapore. This facility is the first of its type dedicated to proton beam micromachining (PBM) on a micron as well as on a nano scale. The design and performance of the facility, which is optimized for 3D lithography with MeV protons, is discussed here. The system has been designed to be compatible with Si wafers up to 6".

Key Words: *Nanomachining, high aspect ratio, nuclear microscope, proton beam, 3D nanostructures.*

I. 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 MEMS devices. High aspect ratio three-dimensional (3D) microstructures with sub-micron details are also of growing interest for optoelectronic devices. Therefore it is essential to develop new lithographic techniques suitable for the production of high aspect ratio 3D micro- and nano-components. One of the more established techniques for 3D micromachining is LIGA [1] 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 [2,3]. In PBM, a high energy (e.g. 2 MeV) proton beam is focused to a sub-

micron spot size and scanned over a suitable resist material (e.g. SU-8 and PMMA), to produce a 3D latent image in a resist material. Of these new techniques PBM is the only technique that offers the capability of direct write high aspect ratio nano- and microstructures. PBM 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 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.

Recently in the Research Centre for Nuclear Microscopy a new dedicated system which is optimized for lithography with protons has been designed and tested. This system is the first of its kind in the world. The focus of this paper will be mainly on the design of the hardware. The system has been designed to be compatible with Si wafers up to 6". The first tests show it is possible to use focused MeV proton beams to do direct write 3D nano structures (e.g. sub 60 nm).

II. PROTON INTERACTIONS WITH RESIST

In PBM the path of a high energy (MeV) 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 larger 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 ($m_p/m_e \sim 1800$). This implies that the path of a proton hardly deviates from a straight line. Since the energy transfer in these collisions is 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 nano- and micro-structures with high aspect ratio.

III. HARDWARE DESIGN

A schematic overview of the proton beam micromachining facility used 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 90° magnet. Beam defining object slits are positioned one meter in front of the switcher magnet. Here we can set a rectangular object that is projected into the target chamber and demagnified with a set of magnetic quadrupole

lenses, located directly in front of the target chamber. Behind the object slits an electro static beam deflection system is installed which serves as a shutter. With the switcher magnet the protons can be steered into the 30° nuclear microscope beam line, which is designed for microscopy purposes and has been used over the last few years for the development of proton beam micromachining.

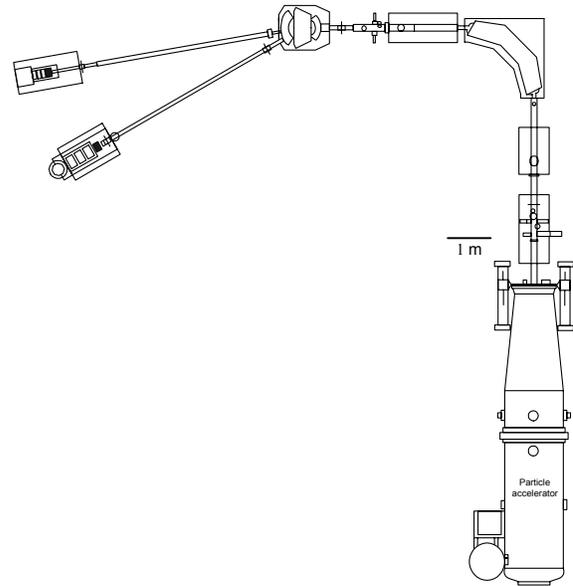


Fig. 1. Proton Beam Micromachining set-up

The protons can also be steered into the 10° beam line, dedicated to micro- and nano-machining. Here a new focusing system is installed which 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 to enhance the system demagnifications (228x60 in x and y). The target chamber and focusing lens system is installed on an optical table to reduce vibrations. 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 system is able to routinely focus the proton beam down to a sub-100nm spot size and use the focused proton beam for maskless direct write lithography.

During exposures the beam is scanned over the resist using a set of electromagnetic scan coils,

located directly in front of the quadrupole lens system. In this way scan fields up to $800 \times 800 \mu\text{m}^2$ can be achieved. In the first tests with the new system only magnetic scanning was operational. Soon we will be able to scan the beam over the full $25 \times 25 \text{ mm}^2$ range of the XYZ stage. The sample will be moved using stage scanning or a combined magnetic scan and stage scan joined via stitching. Provision has been made to install an electro static scanning system. 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. 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 $1 \text{ nA}/\mu\text{m}^2$ 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 scan system utilizes a National Instruments NI 6711 Multi i/o card which has four 12 bits DACs and a minimum update time of $1.0 \mu\text{s}$. Two channels control the scan coils and a third DAC controls the beam deflection. The scan software supports AUTOCAD and Bitmap file format, more details about the scanning system can be found elsewhere [6].

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. To facilitate the production of nano structures with smooth sidewalls more sensitive signals have to be used for normalization purposes. In the new system provision is made to use signals like secondary electron emission and light emission which typically have a much higher yield per proton compared to the number of backscattered events per proton.

IV. Results

In the first tests with this system the focusing power of the new lenses was tested. A beam of 1 MeV protons was scanned over an X-ray mask which contains $1 \times 1 \mu\text{m}^2$ holes. Behind this mask protons were detected which didn't interact with the mask (see fig. 2 top). De-convolution of the line scans perpendicular to the edge of the $1 \mu\text{m}$ hole show a beam spot size of $35 \times 75 \text{ nm}^2$ (see fig. 2 bottom).

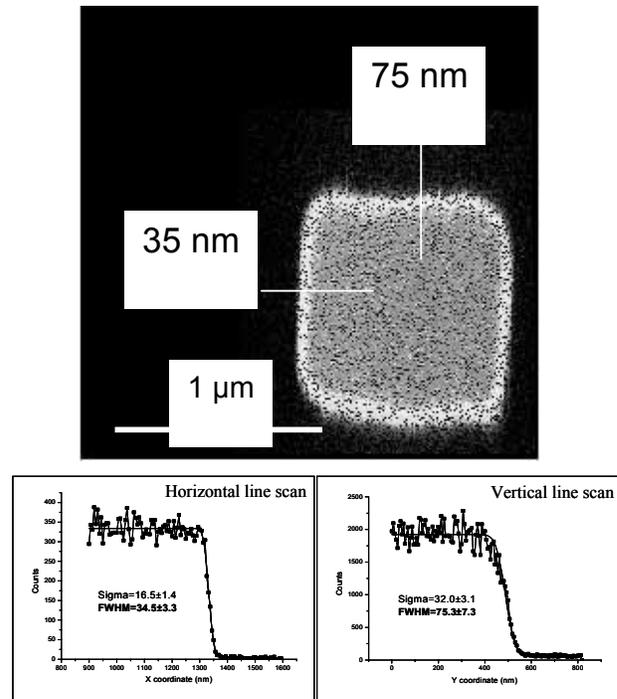


Fig. 2. Beam size measurements

In order to test the lithographic capability of this system, nano structures were written in 2 different PMMA layers spincoated on two Si wafers. One layer was 200 nm thick and the second layer was 2000 nm thick. In these layers a set of parallel lines were written, the lines are 170 nm wide and 1000 nm long. The distance between the lines was varied to test the minimum feature size. Since PMMA is a positive resist the exposed areas will be removed after development resulting in a set of walls with smaller and smaller widths. The narrowest wall that remained in the 2000 nm thick PMMA layer was about 60 nm wide and about 35 nm wide in the case of the 200 nm thick PMMA layer. These results were obtained from AFM and SEM data. The problem in obtaining reliable sizes is the fact

that the PMMA evaporates during SEM imaging. The high aspect ratio of the PMMA structures limits the resolution in AFM.

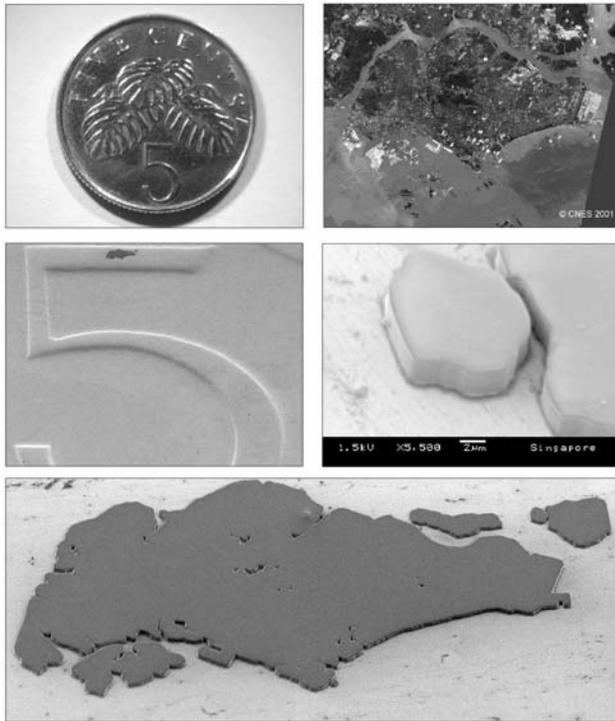


Fig. 3 Map of Singapore produced in SU-8 on a 5 cent coin

In a last example the flexibility of proton beam micromachining is shown. A satellite map of Singapore was scanned, digitized and converted to a scan file. Next a 5 cent coin was coated with SU-8 and the map was written on top of the bar of the “5” of the 5 cent coin (see fig. 3). This is not just an example of the flexibility of PBM but also shows the potential of SU-8 using PBM, in the high magnification inset we see two islands which are separated by less than 500nm. These structures were produced in the 30° nuclear microscopy beam line. Also in the new system the resolution of SU-8 will be tested.

V. CONCLUSIONS

Here we discussed the successful introduction of the worlds first proton beam micromachining (PBM) facility. In this system the proton beam can be focused down to $35 \times 75 \text{ nm}^2$ and directly scanned across a resist, thereby eliminating the need for a mask. Arbitrary shapes can be

fabricated, high-aspect-ratios (close to 100) can be achieved in PMMA resist. The scanning speed in the 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 current magnetic scanning system. Although PBM is in general slower than masked processes for bulk production, it is very suitable for rapid prototyping and the manufacture of molds and stamps that can be used repeatedly for batch and high-volume production.

With the new HVEE 3.5 MV accelerator, deep structures up to $160 \mu\text{m}$ can be produced with 3.5 MeV protons. The new machine, because of its increased beam brightness and high energy stability, has opened the way to even more precise micro and nanostructures.

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. This can be used for fluidic applications [7].

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