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A high resolution beam scanning system for deep ion beam lithography

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Abstract

The technique of Deep Ion Beam Lithography (DIBL) allows the production of high aspect-ratio microstructures in suitable polymer resists (e.g. PMMA) with complex three-dimensional geometries in a fast, direct write process. In conjunction with micromoulding and electroforming, the DIBL-technique may prove extremely useful for the production of microcomponents, micromachines and microelectromechanical systems (MEMS). The present scanning system (OM-DAQ) in use at the Singapore Nuclear Microscope facility is limited to a 256 × 256 pixels raster scan. This system, while adequate for analytical applications, has limitations when machining high resolution structures using DIBL. A new scanning system has been developed in order to overcome this limitation. The new scanning system is based on a DAC PC-card that allows flexible scanning with a resolution of up to 4096 × 4096 pixels. The new system allows the beam to be scanned in specific patterns, which are designed to achieve optimal resolutions. The use of the new scanning system provides a mechanism for translating high resolution digital images into high resolution three dimensional microstructures. Using this system we have produced submicron (300 nm) walls with an aspect ratio approaching 100, three dimensional complex microstructures with smooth walls and corners, and multiple microstructures exposed by repetitive scanning. © 1998 Elsevier Science B.V.

1. Introduction

Technologies for the fabrication of microcomponents, microsensors, micromachines and microelectromechanical systems (MEMS) are being developed rapidly. There are many techniques currently used in microstructure production, most of which are based around surface techniques (i.e. optical lithography, electron beam lithography, low energy ion beam lithography, laser ablation etc.) and applied mostly in silicon based technology. These techniques are often restricted to produce structures with depths of only a few micrometers. To produce three-dimensional deep structures requires a probe which penetrates deeply into the substrate. One such technique is the LIGA process [1,2], where synchrotron X-ray radiation is passed through a mask, and the transmitted X-rays are used to expose a pattern in high density PMMA. Chemical developing is then carried out and the exposed part of the material is removed. Using LIGA, microstructures which have

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a large structural height (up to several millimetres) with an aspect ratio over one hundred, have been successfully produced.

We have successfully used high energy (2 MeV) protons from the National University of Singapore (NUS) nuclear microscope facility to micromachine three-dimensional structures in PMMA, using a direct write process [3]. The range of 2 MeV protons in PMMA is 63 μm which allows the production of high aspect ratio structures. The scanning system used (OMDAQ) in this work has a maximum resolution of 256×256 pixels, which although adequate for analytical mapping, has limitations when high resolution micromachining is required. Described here is the development and application of a new scanning system specifically designed for Deep Ion Beam Lithography (DIBL).

2. Experimental

The exposures presented below were carried out at the Nuclear Microscopy Laboratory at the National University of Singapore [4], where state-of-the-art spot sizes of 100 nm for low current applications, and 400 nm spot sizes for high current (100 pA) applications, can be achieved for 2 MeV protons [5]. The NUS nuclear microscope is built around an Oxford Microbeams endstation OM2000 and a single ended HVEC AN2500 Van De Graaff accelerator. A software package OMDAQ handles the data acquisition and data storage, and controls the scanning of the beam over user defined areas. The OMDAQ scanning system, originally designed for analytical work, raster scans the beam using a magnetic box deflector over the sample using a resolution of up to 256×256 pixels. This relatively low scan resolution imposes limitations when applied to high resolution direct-write lithography. These limitations have been overcome by the development of a new scanning system of much higher resolution. Instead of using a matrix formulation for pattern definition, a standard vectorial graphic file is used to define the pattern. The scan generator system utilises a Keithley ADD-16 DAC card, with a resolution of 12 bits per channel and a minimum upgrading time of 300 μs.

The scan resolution of the new system can be set up to 4096×4096 pixels thereby allowing much higher scan resolutions to be implemented, resulting in smoother edges. In addition to the simple raster mode scanning operation, a new scanning algorithm has been implemented based on a 'turtle' scanning strategy [6]. Using raster scanning the beam rasters across the area to be scanned, remaining for a preset time on pixels that are to be exposed (Fig. 1(a)). In the raster mode, the beam is moved rapidly across regions not meant to be exposed, thereby exposing these regions to a small residual dose. With the new 'turtle' algorithm the beam follows a meander path around the pattern in the area scanned so as to minimise the number

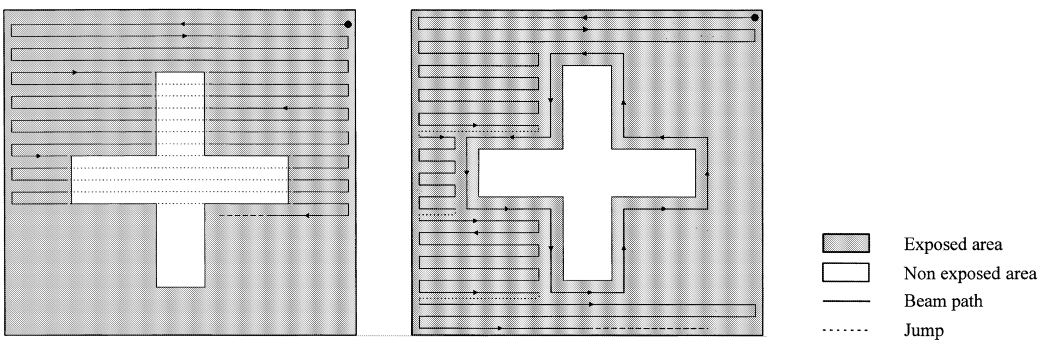

Fig. 1. (a) Path followed by the beam in raster scan mode. The jumps of the beam over the pattern produce residual exposures. (b) Path followed by the beam in 'turtle' mode. With the new algorithm the beam follows a meander path around the pattern. The number of jumps over points that should remain unexposed is minimized.

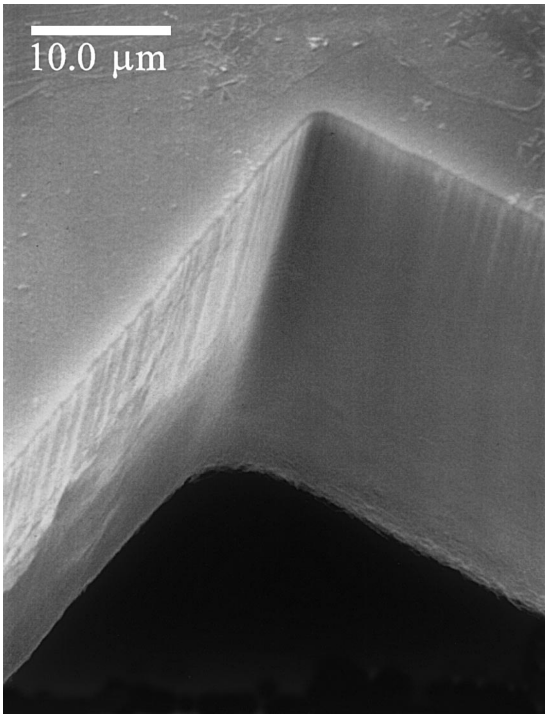

Fig. 2. SEM micrograph of a corner of a cross scanned. Both edges have the same level of smoothness. The small defect visible in the top edge is due to a fault in the bulk of the PMMA.

of jumps over points that should remain unexposed. The new software also allows us to draw separately the outline of the figures to be scanned (Fig. 1(b)). This strategy improves the sharpness and homogeneity of the edges.

The accelerator used in the present work is a belt driven machine, with an inherent high energy instability. This causes the beam intensity to fluctuate rapidly, thereby making the micromachining of smooth walls and edges difficult. One way of reducing the effects of beam intensity fluctuations is to normalise the proton dose for each pixel. Since the insulating character of the PMMA precluded the use of the monitored beam current for normalization, we used instead the RBS signal from a large surface barrier detector (630-msr solid angle) positioned close to the target. This normalisation system however was not very efficient; full exposure occurred at only 12 RBS events per square micrometer. This low number of counts also prevented the use of the full resolution of the scanning system when small areas were scanned.

A direct-write 2 MeV proton beam focused to 1 μm was used to expose a set of different patterns in a thick (2 mm) high density PMMA. The currents used were ranging between 1 and 100 pA and the

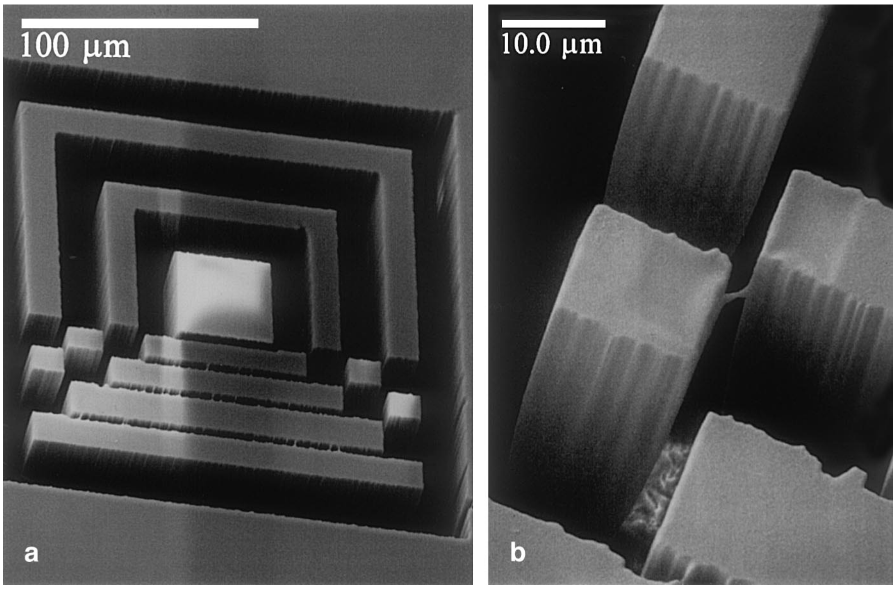

Fig. 3. (a) SEM micrograph of walls. (b) Magnified view of the two pillars in the lower left of (a). The small structure between the two pillars is thought to be due to a fault in the bulk of the PMMA.

proton dose was optimised at 80 nC/mm^2 [3]. After exposure, the PMMA was developed following the procedure given in [3].

3. Results

A cross pattern was scanned using the 'turtle' mode over a square area of 400 μm at a scan resolution of 512 × 512 pixels. Fig. 2 shows an electron micrograph of one of the corners of the developed structure. Both edges have the same level of smoothness, and the results are much superior to earlier machined structures as shown in [3].

The microstructure shown in Fig. 3(a) was also scanned using the 'turtle' mode at a resolution of 512 × 512. The resulting structures exhibit relatively sharp and well-defined edges. However, as can be observed from Fig. 3(b), a magnified region of the smaller structures indicates walls that are not smooth. These defects are due to low proton dose caused by beam intensity fluctuations which were not sufficiently compensated by the normalisation system.

The limit in resolution in the sense of the smallest track that can be written is defined by the beam spot size. However, the minimum size of a structure that can be produced is not necessarily limited by the dimensions of the beam. This is demonstrated in Fig. 4. A set of parallel lines with decreasing distances between them was exposed. The remaining unexposed PMMA then forms a series of narrowing walls which took the form of suspended bridges due to the undercut from the end of the range damage discussed in [3]. The lines were scanned over a region of 100 × 20 μm using a resolution of 1024 × 200 pixels. The width of these walls is around 300 nm, smaller than the beam size estimated at 1 μm. The depth of the walls was estimated from SEM micrographs (not shown) to be approximately 30 μm, thereby suggesting an aspect ratio approaching 100 for this type of structure.

Fig. 5 is a SEM micrograph of a sixfold-repeated structure of two interlocking gearwheels and a gear bar. This exposure was carried out in raster mode at a resolution of 512 × 512 pixels, and demonstrates the flexibility of the scanning system for producing multiple components.

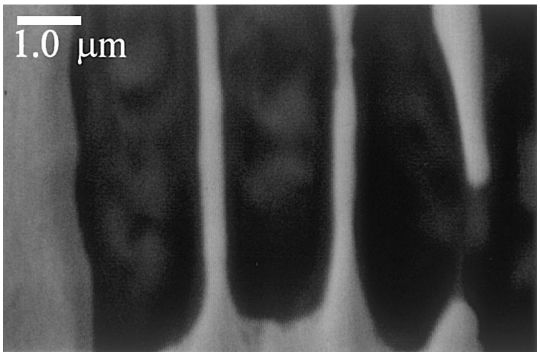

Fig. 4. SEM micrograph of 300 nm walls with an aspect ratio approaching 100.

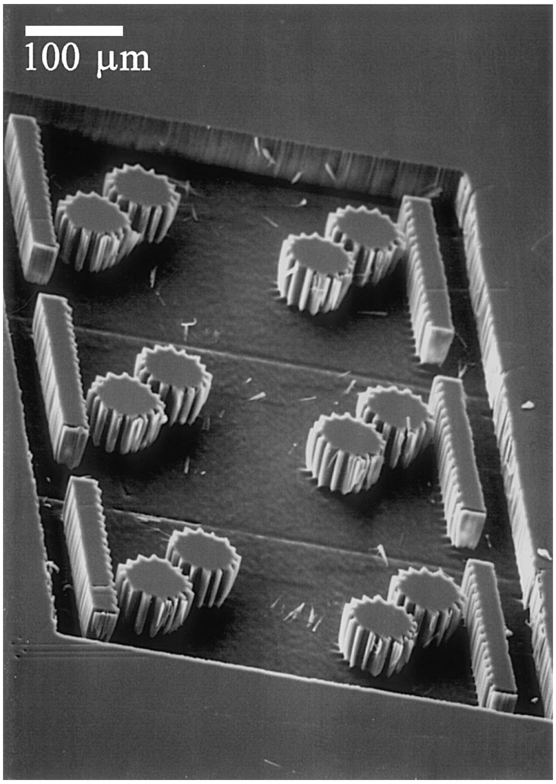

Fig. 5. SEM micrograph of a sixfold-repeated structure of two interlocking gearwheels and a gear bar. The side length of the exposed region is 400 μm.

4. Conclusions

A new scanning system specifically designed for DIBL has been developed based on a Keithley ADD-16 DAC card, with a resolution of 12 bits per channel and a minimum upgrading time of 300 μs. The scan resolution of the new system can be set up to 4096 × 4096 pixels thereby allowing much higher scan resolutions to be implemented, resulting in smoother edges. In addition to the simple raster mode scanning operation, a new scanning algorithm has been implemented based on a 'turtle' scanning strategy.

Exposures taken using this new scanning system enabled smoother walls to be produced, allowed submicron walls to be machined with aspect ratios up to 100, and demonstrated the flexibility of the scanning system for producing multiple components. Further improvements that will enhance the quality of micromachining include the use of fast electrostatic beam blanking for stepping the beam over areas that do not require exposure, the utilisation of electrostatic rather than magnetic scanning, and more importantly, reducing beam intensity fluctuations.

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