High Resolution Nanolithography using Focused Ion Beam Scanning Electron Microscopy (FIB SEM)

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ABSTRACT

State-of-the-art focused ion beam (FIB) technology combined with high-performance scanning electron microscopy (SEM) is making a big impact on nanotechnology, particularly with the ability to use either focused ions or electrons to perform advanced nanolithography. Achieving the highest standards requires an understanding of the physics and chemistry of the system as a whole, which contains ions and electrons of various energies and origins, substrates with a range of electrical and mechanical properties, and reactive gases capable of specific effects on sputtering and re-deposition. We have built up a detailed knowledge of these complex parameters and, accordingly, have developed new strategies, allowing us to generate high resolution nanolithographic structures down to a few nanometers. We compare and contrast different strategies in order to demonstrate the importance of factors such as single- or multi-pass execution as well as milling order and time-dependent considerations.

Keywords: Nanofabrication, nanolithography, rapid prototyping, DualBeam, FIB SEM

1 INTRODUCTION

FIB milling of patterns in any kind of material and the precise beam induced deposition of various materials, in one single instrument, are recognized as novel ways of carrying out true, rapid prototyping. The capability to observe the patterning process live and to immediately image the resulting structures with high resolution (see, for example, Fig. 1) offer unique control over the process. Pattern modifications can be carried out instantaneously and prototype functionality can be tested before the final layout of a device is established for batch fabrication. Beam induced deposition of different materials can be combined with FIB milling without the need of several aligned lithography steps; stacks of dissimilar materials can be structured in one single milling process; patterns can be added to existing structures on a substrate (e.g. on nanoimprint stamps). Patterned substrates are immediately available for further processing or characterization. Once a prototype has been tested successfully, batch nanofabrication processes can be integrated with electron beam lithography using the SEM column of the instrument. The capability to pattern almost any material and fabricate layers composed of dissimilar materials makes the FIB highly versatile [1, 2, 3]. The ability to rapidly prototype and perform resist patterning for nanofabrication in one instrument holds the potential to deliver much faster proof-of-concept results for devices and point the way towards volume manufacturing.

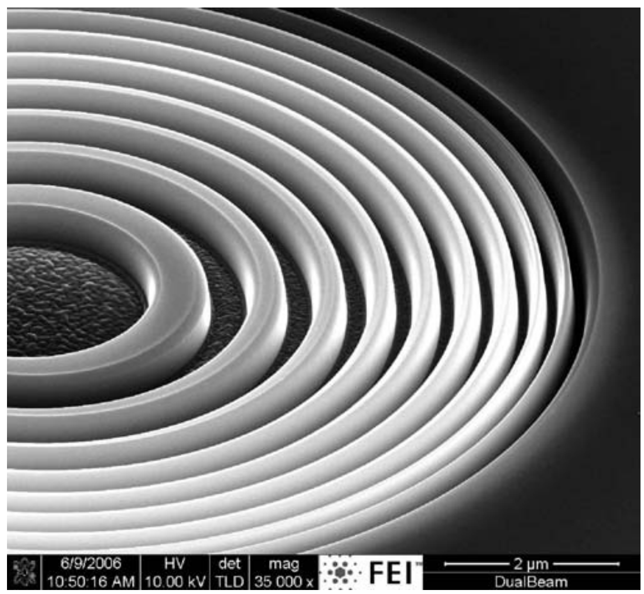

Figure 1 : Fresnel zone plate milled into silicon using a beam of focused gallium ions, demonstrating excellent side wall quality and high aspect ratio

2 ION BEAM LITHOGRAPHY

The pattern engine that is used for electron beam resist exposure can also be used for direct FIB patterning. The apparent similarities in controlling and steering often lead researchers to carry forward electron beam lithography exposure strategies as a technique for FIB pattern execution. This, however, neglects fundamental differences, such as exposure to certain doses before resist development in electron beam lithography and the instantaneous removal or deposition of material with a FIB [4, 5]. The following sections illustrate the significance of adequate pattern execution for successful FIB patterning.

2.1 Parallel, serial and single pass milling

The profile of a single point milled into any substrate will partly be determined by the profile of the FIB itself. On the other hand, since the FIB immediately sputters away substrate material, a void forms while the FIB continues milling at the same position. Consequently ions hit the sloped sidewalls of the forming void, especially at longer pixel dwell times. As sputter yields depend on the angle of the incident ions, so milling rates depend on pixel dwell time. Another aspect that needs to be taken into consideration is the re-deposition of sputtered material that will occur inside the milled structures.

For illustrative purposes a Y-junction of 100 nm wide trenches, 200 nm deep, was milled into silicon. Based on ion beam current, accelerating voltage and substrate material, a pitch of 8.5 nm was calculated and automatically set in order to have a 50% overlap of adjacent pixels. The trenches were patterned in a serpentine sweep. Figure 2a shows the resulting pattern when all individual pattern elements are milled in parallel and with multiple passes of the FIB as per default conditions, in this case 1 µs dwell time, 882 passes.

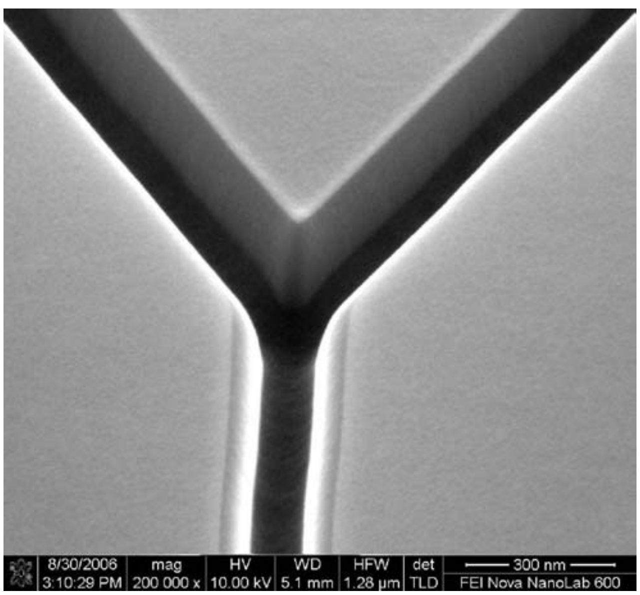

Figure 2a : Parallel multi-pass milling

Figure 2b shows the same pattern milled with multiple passes as in Figure 2a, but this time serially: milling the legs of the Y-junction one after the other. Figure 2c shows the result when the pattern is executed using an electron beam lithography exposure strategy, the total dwell time per pixel being delivered in one single pass, here in one pass at 882 µs dwell time.

The parallel multi-pass milling of Figure 2a results in a trench pattern that could directly be used in a fluidic device for instance. The serial multi-pass milling in Figure 2b leads to artifacts at the junction, while the single-pass milling in Figure 2c shows evident re-deposition on the sidewalls leading to a V-shaped line profile and, again, artifacts at the junction.

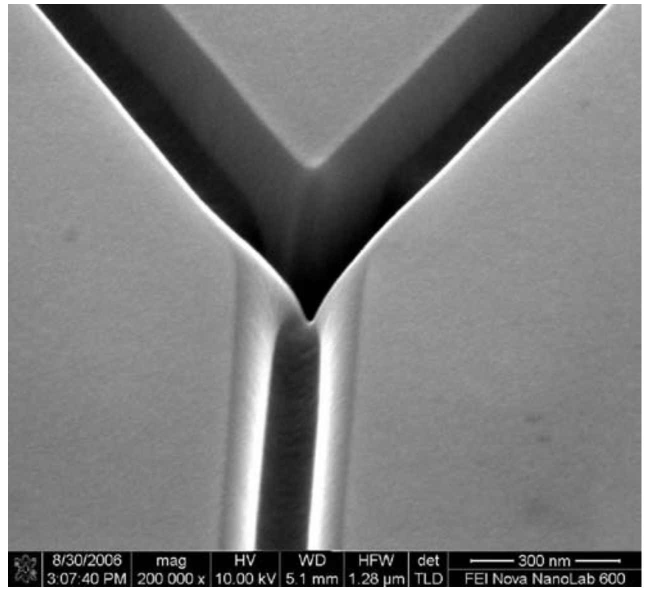

Figure 2b : Serial multi-pass milling

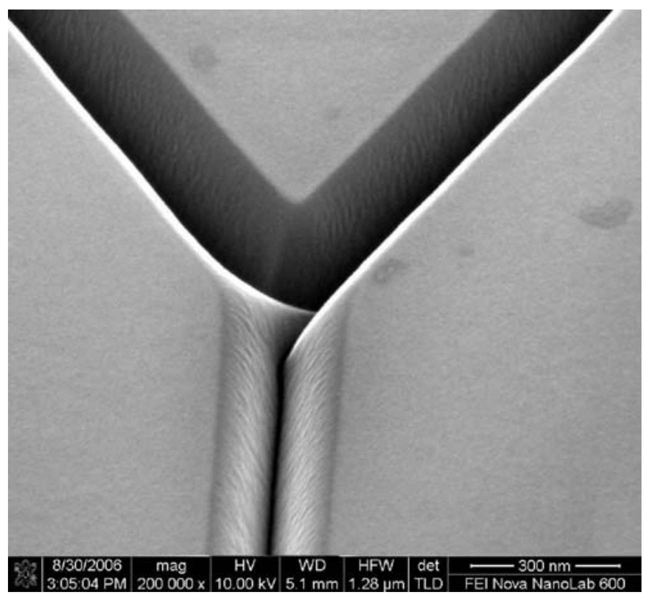

Figure 2c : Single-pass milling, adopting an electron beam lithography strategy

The short pixel dwell times in multi-pass milling avoid the formation of strong topography in one pass, thus yielding homogeneous pattern depth. This pass is repeated until the target depth is reached. The milling of the entire pattern until completion prevents the build-up of re-deposition. In contrast, a single-pass pattern exhibits pronounced milling artifacts which reflect the direction of the sweeps and the leading edge.

2.2 Milling order and re-deposition

Patterns that comprise features across a larger range of critical dimensions are most efficiently milled with different ion beam currents for optimization of the overall milling time. The necessary changes of ion beam current make serial multi-pass milling inevitable. In this case the actual milling will lead to re-deposition of sputtered substrate material into the previously milled patterns, making the milling order of crucial importance for successful prototyping. A small pattern milled next to a large pattern will only cause negligible re-deposition as little material is removed and deposited across a relatively large area. A small pattern next to which a large pattern is milled will strongly be affected by re-deposition as more material is removed while milling the large pattern.

The effect of the milling order is shown in Figures 3a & 3b. A series of 9 boxes were milled 400 nm deep into silicon. The center box was 200 nm wide, the pair either side of to it 400 nm, continuing 600 nm, 800 nm and 1000 nm, respectively. Figures 3a & 3b show the central part of this pattern in greater detail. In Figure 3a the central 200-nm box was milled last yielding a smooth bottom and clean side walls; in Figure 3b the milling order was reversed, i.e. the 200 nm box was milled first followed by all other boxes. In the latter case re-deposition of all subsequently milled boxes can clearly be seen on bottom and side walls.

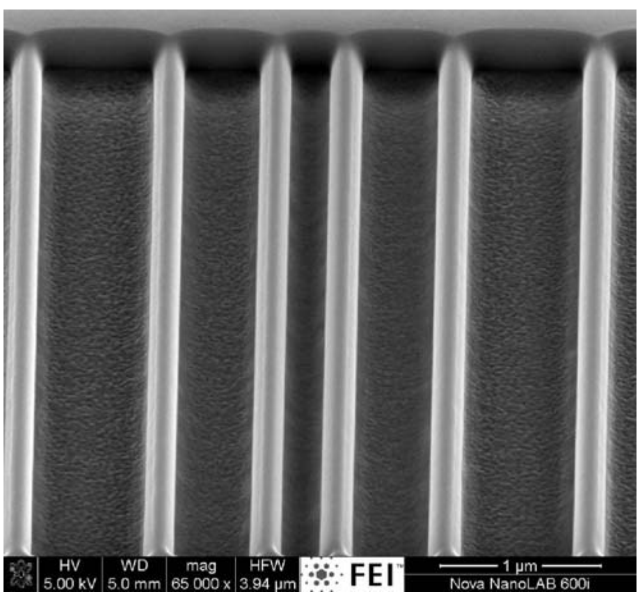

Figure 3a : A clean central 200 nm box as a result of being the last element in the milling order

The prototyping of individual devices with the FIB often takes only a few minutes per layer. Larger arrays of devices however will need considerable patterning times. In order to avoid possible drifts which could degrade the definition of individual pattern elements, grouping of pattern elements to be milled in parallel is considered the best compromise between pattern definition and placement accuracy. When mix-and-match strategies require the overlaying of a FIB pattern with an existing pattern, the FIB pattern can either be placed based on quick full-frame image recognition or the registration of alignment marks. For registration of alignment marks however, it has to be taken into account that the FIB is milling the alignment marks during registration.

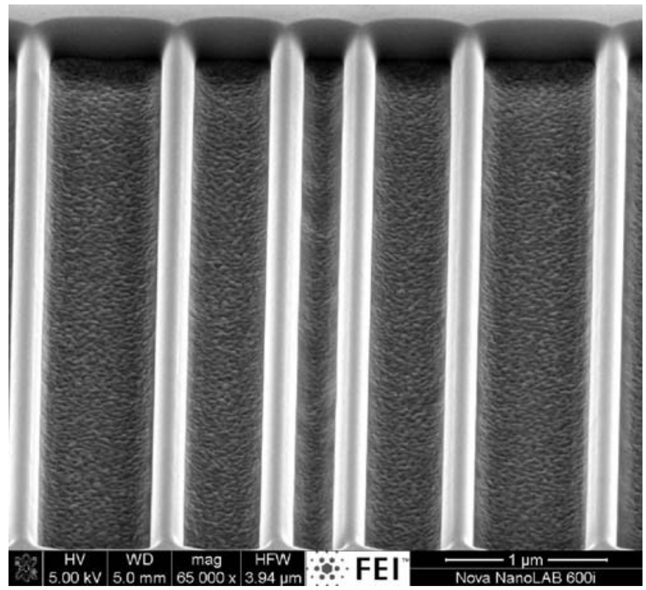

Figure 3b : The central 200 nm box was milled first in this case and shows accumulated re-deposition from the subsequent milling of all other boxes

3 BEAM-INDUCED CHEMICAL VAPOR DEPOSITION

In conjunction with a suitable gas delivery system, the FIB can be used to form localized, site-specific chemical vapor deposition of materials such as tungsten, platinum, gold, carbon and silica. It is therefore possible to create multi-layered devices in a variety of configurations. Figure 4a shows a plan view of such a FIB-assisted CVD structure, while Figure 4b shows a side view, after cross-sectioning with the FIB.

The properties of materials deposited by beam induced deposition can be substantially different to materials deposited by conventional nanofabrication techniques. The inclusion of molecules of the gaseous precursor can generate high contents of carbon in the deposits (deposits typically also include gallium from the ion beam). Gallium implantation and amorphization of a surface layer on sidewalls and structure bottom need to be considered. However, recent work has shown that the use of very low ion beam accelerating voltages offer a way to significantly reduce the risk of implantation and damage [6].

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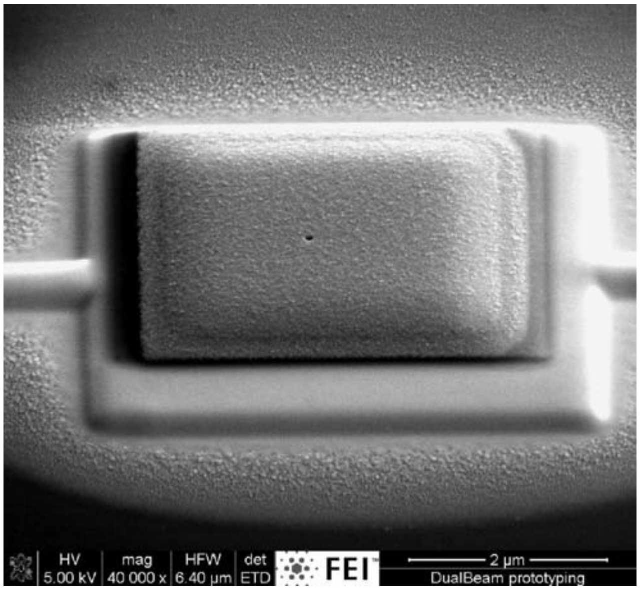

Figure 4a : Intermediate step of a cross-bar architecture intended for self-assembly of alkanethiol-based functional molecules. Bright square and contact lines: W-deposition; buried square: Au deposition; rough deposition on top: SiO_x insulator deposition. As a last step, a 50 nm hole was milled through the SiO_x insulator down to the Au layer to allow selective self-assembly inside the hole

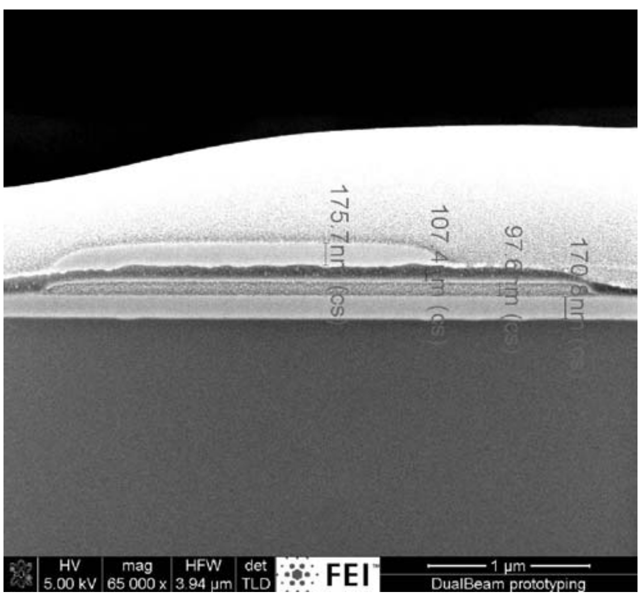

Figure 4b : FIB cross-section through the cross-bar architecture of Figure 3a after top-electrode deposition. The bright layer on top is a Pt deposition for facilitating FIB cross-sectioning. Clearly visible are: W top electrode (176 nm), the SiO_x insulating layer (107 nm), Au layer (98 nm), and the W bottom electrode (171 nm)

Although material properties may be different from the final device made by batch fabrication, FIB prototypes are well suited for electrical testing or catalytic functionality, for instance. Ultimately, FIB prototypes should be seen as a means to shorten development times in the initial and intermediate phase of a research project. Many critical process and application challenges can be tackled while a batch process is still under development.

4 CONCLUSIONS

A dedicated patterning strategy for rapid prototyping with the FIB has been shown to be of crucial importance. The ability to observe the patterning process live with a high resolution SEM gives the operator immediate insight and direct control over the patterning process. In addition, a batch fabrication process can be developed with the electron column as patterning tool for electron beam lithography (not shown).

The combination of rapid FIB prototyping and electron beam lithography in one FIB SEM instrument allows us to choose the most suitable patterning techniques and strategies, offers a means for delivering prototypes to application testing long before batch processes are established and, in parallel, suggests scenarios for nanofabrication in larger volumes.

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