

# Strategies for fabricating nanostructures with focused ion beam technology

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## ABSTRACT

Focused ion beam (FIB) has emerged as an important tool in research in the field of nanotechnology (1). With computer controlled ion beam steering, it is possible to mill complex nanostructures (2). It is also possible to control parameters such as beam current, spot overlap, dwell time and milling sequence. Patterns can be programmed and run on the systems as stream files (.str files). One of the problems that limits the accuracy and resolution of the patterns being milled is the re deposition. Depending on the milling parameters, sputtered ions can travel a distance and redeposit in the structure being milled. In this investigation, the effect of the milling parameters on the fabrication of nano patterns in silicon is evaluated. Another problem with milling patterns is that the beam is not switched off while traveling from one feature in the pattern to the next. This means that with high number of loops the surface between the features is also milled. This makes it necessary to find an optimum between the dwell time which influences re deposition on one hand and the number of loops which can lead to unwanted milling on the other. Results of the milled patterns are presented. Cross sections are investigated to evaluate extent of re deposition. Milling strategies for optimum results are discussed.

## 1 INTRODUCTION

One of the primary applications of FIB is milling of material on micro or nano scale. Commercial focused ion beam systems (FIB) use Ga ion beam. The milling is a process of sputtering atoms with energized Ga ions. The energetic ions striking the surface of the specimen eject the atoms on the surface. This results in milling of the specimen surface. Removal of atoms from the substrate is dependent on the energy of the incident ions.

The yield or the number of atoms removed first increases slowly with energy, then flattens out, and then decreases at about 50 keV. (3). Typical acceleration voltage used in most FIB equipment is 30kV which gives optimum milling performance. If  $\rho$  is the density of the material (atoms/cm<sup>2</sup>) and  $d$  is the depth of milling, and  $\Delta$  is the ion dose of ions/cm<sup>2</sup> then the yield is given by

$$Y = \rho d / \Delta \text{ atoms/ion} \quad (1)$$

In practice however the actual yield is lower than the theoretical yield. Several factors affect the actual yield.

Leaving aside the geometrical factors, most important factor is re deposition. All the ejected atoms do not travel away from the site of sputtering. Some are re deposited depending on their angle of ejection and the energy. When a particular area is milled with FIB, the beam is not stationary at one location but scans the area either with a raster scan or a serpentine scan. With every pass, sputtering takes place at a particular location. When re deposition takes place, sputtered atoms from the subsequent location deposit at the first location. During the second pass, this material is sputtered away with the substrate material. This process of milling and re deposition continues with time till it reaches what we may call a steady state where no more atoms can escape from the area. At that point the process of milling does not proceed further. The shape of the feature is greatly influenced by this phenomenon. One more aspect which complicates this process is that the sputtering properties of the re deposited material differ from the original material. When ejected atoms re deposit, the original structure of the material is not retained. For example, crystalline Si is amorphous as re deposited material.

## 2 EXPERIMENTAL

To determine the re deposition effect on milling, a pattern of 1  $\mu^2$  was selected. The milling operation was carried out with FEI make Nova-600 nanolab equipment. Milling was performed with a raster scan. The beam overlap was 50 %. The pattern was milled starting from 1 min up to 10 mins. After milling, standard well established FIB cross sectioning method was used. Platinum was deposited to ensure that the shape of the milled area was preserved. Available cross sectioning software feature was used to make an initial cut followed by cleaning cross section milling. The cross sections were viewed with high resolution SEM available in the system.

As mentioned earlier, re deposition is a function of dwell time at a particular milling location. To evaluate the effect of dwell time (and number of loops) on a pattern, stream files were programmed with dwell times of 0.001ms, 0.01ms, 0.1ms and 1ms. The dose was kept constant by adjusting the number of loops. The scan direction for every feature was maintained from left to right.

### 3 RESULTS AND DISCUSSION

The results of milling of a feature of  $1 \mu^2$  square with 1 min and 10 mins at 48 pA can be seen in fig 1 and 2. It is clear that even after 1 min of milling of a 1 micron square with 48 pA, there is rounding of the edges. This is because of the Gaussian shape of the beam. With 10 mins of milling the effect is even more prominent. The tail of the beam has caused substantial milling around the edges of the pattern. Some amount of re deposition at the rim of the feature can also be clearly seen. With 10 mins of milling, there is almost no further removal of material. The depth of milling with time can be seen in Fig. 4. For all experiments the substrate material chosen was Si.

It is clear from fig. 3 that after about 10 mins of milling under the given conditions, the milling virtually stops. This is the result of re deposition. The sputtered material cannot escape from the bottom of the milled feature.

While milling, the time the beam spends at a particular location is called dwell time. This can be programmed in the stream file. As seen from the previous results, the time spent at a location also affects the re deposition. Four different stream files were programmed with different dwell times at a pixel. The total dose of ions was kept constant. This meant that the number of loops was adjusted to keep the dose constant. careful observation clearly showed with dwell time of 0.001 ms, there was a distinct milling of the edge of the pattern on the right. This was the direction of scanning. The beam does not switch off between the two features. Since the number of loops are very high, there is milling of the intermediate area. With a dwell time of 1 ms, this effect is not visible.

The cross sections reveal the effect of the dwell time on re deposition in the depth of the milled feature which is dramatic. The cross sections can be seen in fig. 4 to 7

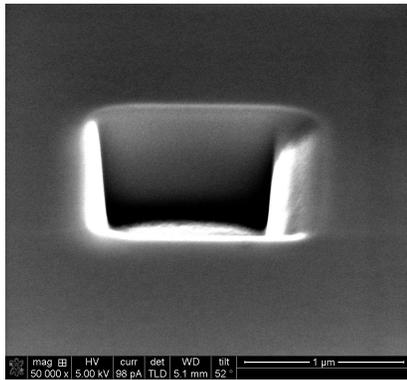


Fig. 1 Feature after 1 min milling

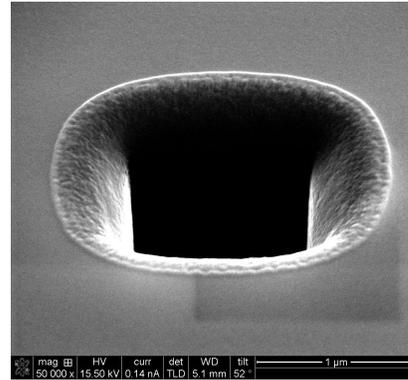


Fig. 2 Feature after 10 mins milling

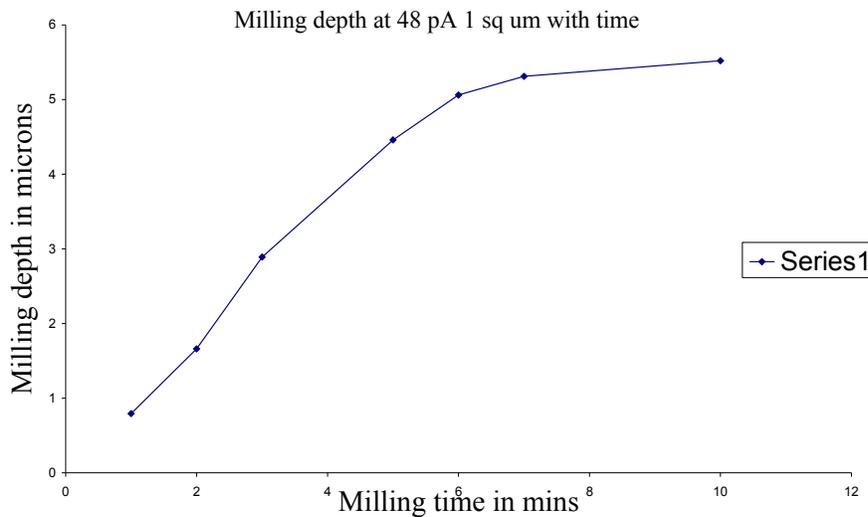


Fig. 3: Depth of milling with milling time

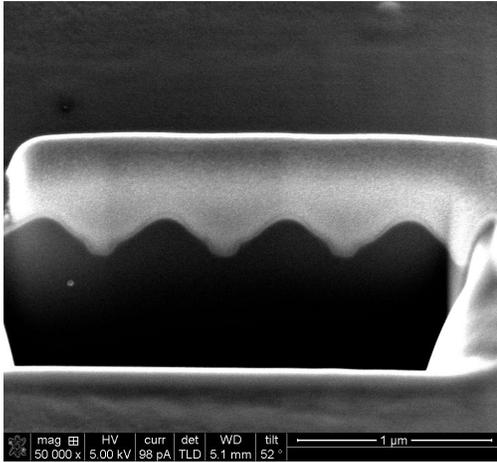


Fig. 4: Cross section: Dwell time 0.001 ms

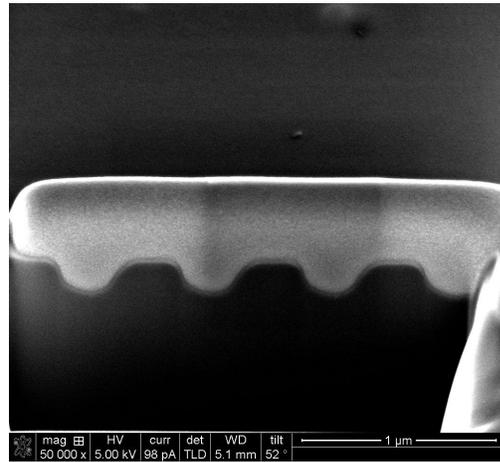


Fig. 5: Cross section: Dwell time 0.01 ms

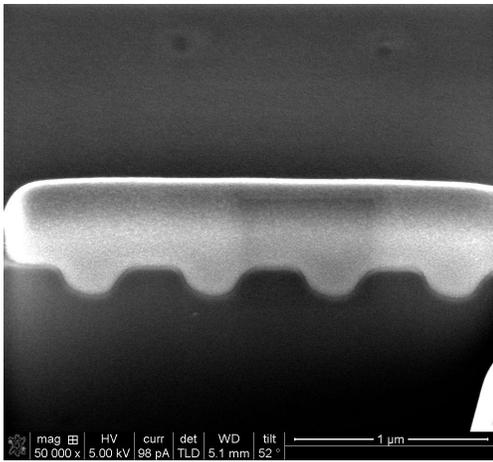


Fig. 6: Cross section: Dwell time 0.1 ms

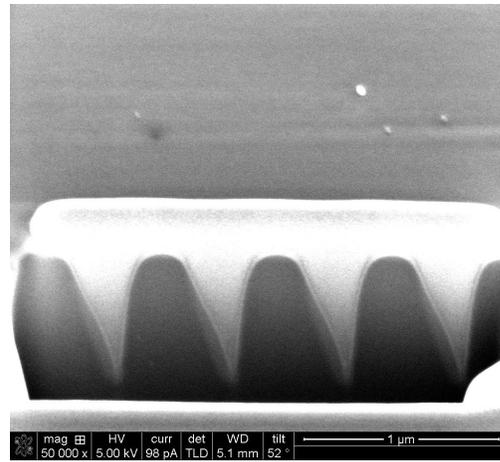


Fig. 7: Cross section: Dwell time 1 ms

With dwell time of 0.001 ms, there is milling of material which re deposits and is re milled over and over again resulting in a profile that is deeper in the middle than on the edges. With increasing dwell time, the profile changes becoming more well defined. With very high dwell time of 1 ms, the profile is much deeper. There is only one pass from left to right. Here the effect of re deposition is clearly visible. As the beam passed from left to right, the milled material from the right of the feature re deposited on the left wall. This is even visible due to difference in contrast in the re deposited material. It is clear from this experiment that the dwell time has to be adjusted to an optimum to be able to fabricate nanostructures which will best confirm to the intended design.

There have been some attempts to simulate the process of milling (4,5). The large number of parameters and lack of information about the sputtering rates of the re deposited

material as well as the 'sticking factor' of the material makes it extremely difficult to model the process. The geometry of the feature that is being milled is also a very important parameter. Milling current determines the rate of milling and the beam diameter. Different materials can show different re deposition effects. The manner of scanning while milling patterns (serpentine or raster), also affects the accuracy of the pattern (6). Charging of the specimen will also influence the process. In spite of considerable knowledge generated in recent years, milling process is still not well understood and at present no predictive model exists that can apply to all materials and geometries. It is still possible to fabricate nanostructures with FIB with reasonable accuracy and reproducibility. Below are two such examples. Fig. 8 shows a pattern milled in chromium layer on Silicon and Fig. 9 shows a diffraction grating milled on a wave guide on silicon.

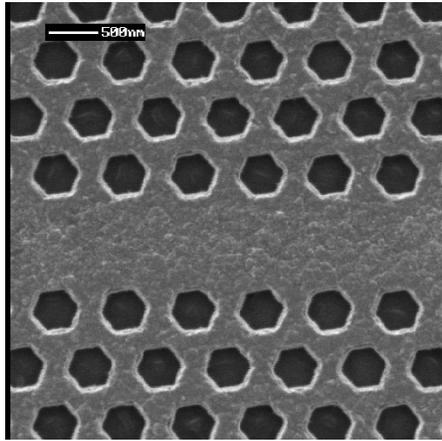


Fig. 8 Pattern milled in Chromium layer

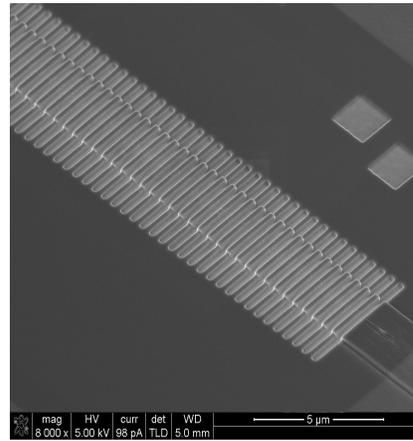


Fig. 9 Grating milled in a waveguide

#### 4 CONCLUSIONS

- Milling of patterns is a complex process governed by a large number of parameters
- In spite of the knowledge generated over the years the process is not fully understood
- There is still no mathematical predictive model of this complex process
- With selection of correct parameters through experimental process it is possible to fabricate reasonably accurate nano structures
- Further work is required to extend the understanding of this process.

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#### 5 REFERENCES

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