Optimization of Nano-Machining With Focused Ion Beams

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ABSTRACT

FIB milled lines can be optimized for nano-machining with an understanding of ion-solid interactions. In particular, the incident angle of the ion beam with respect to the sample surface as well as the direction of milling can affect the shape and aspect ratio of the FIB milled cut.

Keywords: FIB, nano-machining, ion milling

1 INTRODUCTION

A DualBeam (DB) instrument consists of a focused ion beam (FIB) and scanning electron microscope (SEM) on the same platform. A 4k x 4k digital pattern generator can be utilized to automate precise movements of either the ion beam or the electron beam. FIB milling can be used for site-specific nano-machining of surfaces. In addition, by introducing a suitable precursor (e.g., organometallic gas) into the DB chamber, site specific metal lines can be produced via ion beam or electron beam assisted chemical vapor deposition processes. Many investigators have used DBs or FIB instruments to create nano-structures by either FIB milling or FIB/SEM deposition [1]. As will be shown below, the aspect ratio of a FIB milled line can be controlled by altering the incidence angle of the ion beam with respect to the sample surface through an understanding of ion-solid interactions.

2 EXPERIMENTAL TECHNIQUES

Lines of 1 μm in length were FIB milled into Si using 30 keV Ga^+ ions with a beam current of 100 pA at a nominal depth of 250 nm at either 52° or 0° incidence angle using an FEI Strata 400S DualBeam instrument. The lines were first filled in with electron beam deposited Pt first to protect the line, followed by FIB deposited Pt to facilitate cross-sectioning. The lines were cross-sectioned using conventional FIB methods [1]. The geometry of the lines were analyzed by SEM and compared with theoretical ion-solid interactions as shown below.

FIB milling is flexible enough such that either the ion beam dwell time, the depth of mill desired (i.e., time that the beam is on), and/or the number of beam passes can be defined. These parameters are interrelated and thus, changing one variable affects the others. In the next series of experiments, a 1000 pA ion beam was milled into Si at various incident angles at a set time (i.e., depth), using just one beam pass, but altering the start and end direction of the ion beam. These lines were FIB milled into Si using 30 keV Ga^+ ions with a beam current of 1000 pA at either 52° or 0° incidence angle using an FEI Quanta 200 3D DualBeam instrument using only a single beam pass.

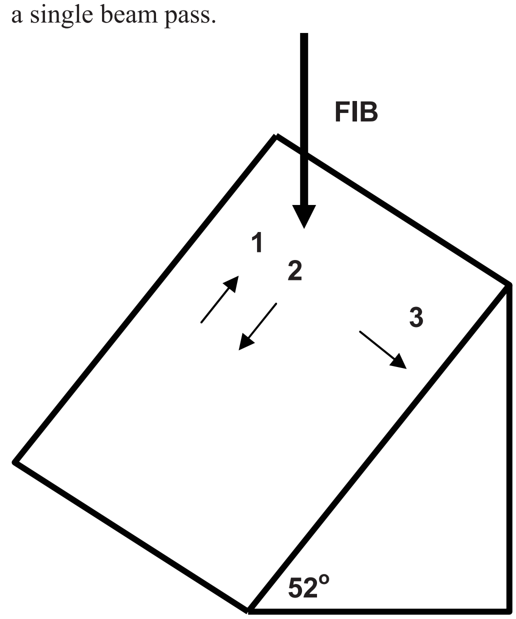

Figure 1: A schematic diagram of single pass lines FIB milled into Si.

A schematic diagram of the single ion beam passes performed at an incident ion angle of 52° is shown in figure 1. Each line was FIB milled either up the slope as shown by arrow 1, down the slope as shown by arrow 2, or across the slope, as indicated by arrow 3. The lines were then filled in with electron beam deposited Pt to protect the line, followed by FIB deposited Pt.

The lines were cross-sectioned using conventional FIB methods [1]. The geometry of each line was analyzed using an FEI Quanta 600 FEG SEM and compared with theoretical ion-solid interactions as presented below.

3 RESULTS AND DISCUSSION

Figure 2 shows results from TRIM simulations of ion trajectories of 30 keV Ga^+ ions into Si [2]. The images in figure 2 show the ion trajectories at 52^o (top) and 0^o (bottom) incidence angle. Note that the ion trajectories at 52^o incidence angle are closer to the sample surface, resulting in a higher sputter yield (9 atoms/ion for 52^o vs. 3 atoms/ion for 0^o) and less damage to the surface. Since the sputter yield is higher at higher incidence angles, one would expect that, for all other FIB parameters kept constant, the ion beam would create a deeper cut, thereby creating a higher aspect ratio FIB milled line.

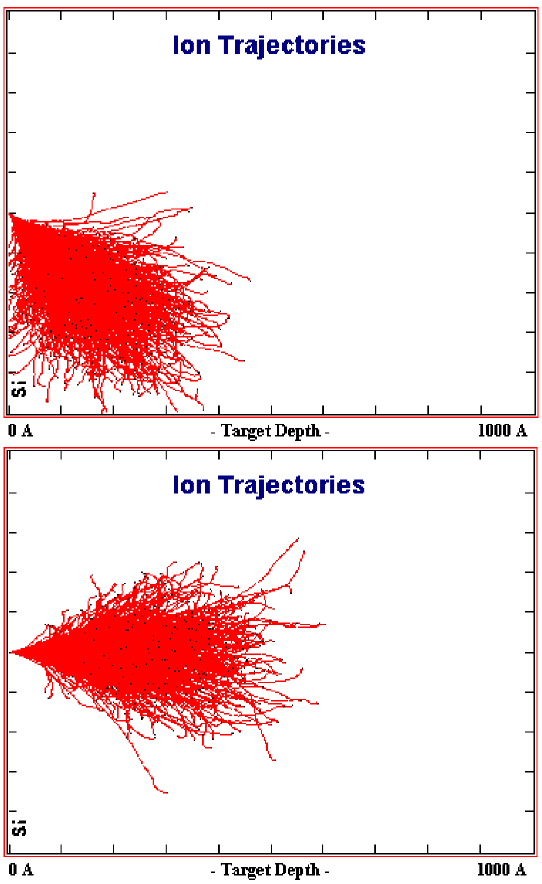

Figure 2: TRIM simulations of ion trajectories of 30 keV Ga into Si at (top) 52^o incidence angle and (bottom) 0^o incidence angle.

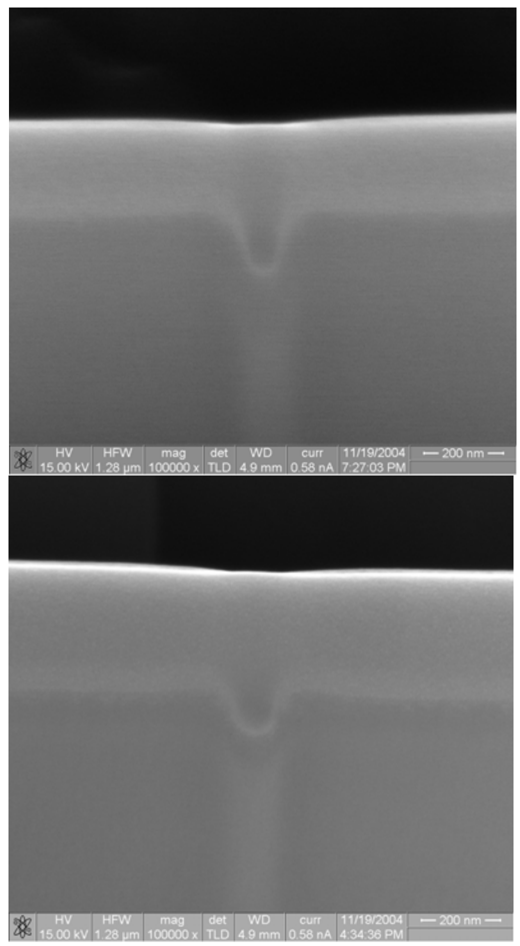

Figure 3: (top) FIB line milled at 52^o incidence angle (DB stage tilt of 0^o). (bottom) FIB line milled at 0^o incidence angle (DB stage tilt of 52^o).

Figure 3 shows SEM images of FIB milled cross-sections of FIB milled lines performed at 52^o incidence angle (top) and 0^o incidence angle (bottom). The differences in the aspect ratios of the FIB milled lines are evident in the SEM images in figure 3, where the 52^o incidence angle cut shows a deeper cut with an overall improvement in the aspect ratio of the cut from ~ 2:1 to 3:1. Since different materials exhibit different collision cascade characteristics which also vary with incidence angle [3], it is expected that different FIB milled aspect ratios will vary with material as well as incidence angle that are consistent with ion-solid interaction theory.

A cross-section SEM image of a FIB line milled in a single line pass up a 52^o slope is shown in figure 4 (top). A cross-section SEM image of a FIB line milled down a 52^o slope is shown in figure 4 (middle), and a cross-section SEM image of a FIB line milled across the slope is shown in figure 4 (bottom). The dimensions shown in figure 4 have been corrected for SEM observation tilt angle.

Note that the FIB line milled up the slope (figure 4 top) is much shallower than the FIB line milled down the slope (figure 4 middle). This is consistent with the shape of the ion trajectories shown in figure 2. When the beam traverses up the slope, a new collision cascade is generated with each new position of the beam, and thus, the sputtered material is defined by the new position of each collision cascade.

However, when the beam traverses down the slope, each position of the beam overlaps a region devoid of material formerly removed by the previous collision cascade. Thus, milling down the slope occurs on an open sidewall, and the overall effect is that a deeper cut is produced when milling is performed down the slope of the inclined surface. In addition, the aspect ratio of the milled cut performed down the slope is greater than the aspect ratio of the milled cut performed up the slope. When a single beam traverses across the slope as shown by the SEM image in figure 4 (bottom), its leading edge angle is consistent with the incident angle defined by the ion-solid interactions. Milling on the trailing edge of the beam is diffuse since the side of the beam can interact with the sample surface, creating a larger hole opening in the top portion of the cut. Note also that the depth of the cut obtained across the slope (figure 4 bottom) is consistent with the depth of cut performed down the slope (figure 4 middle).

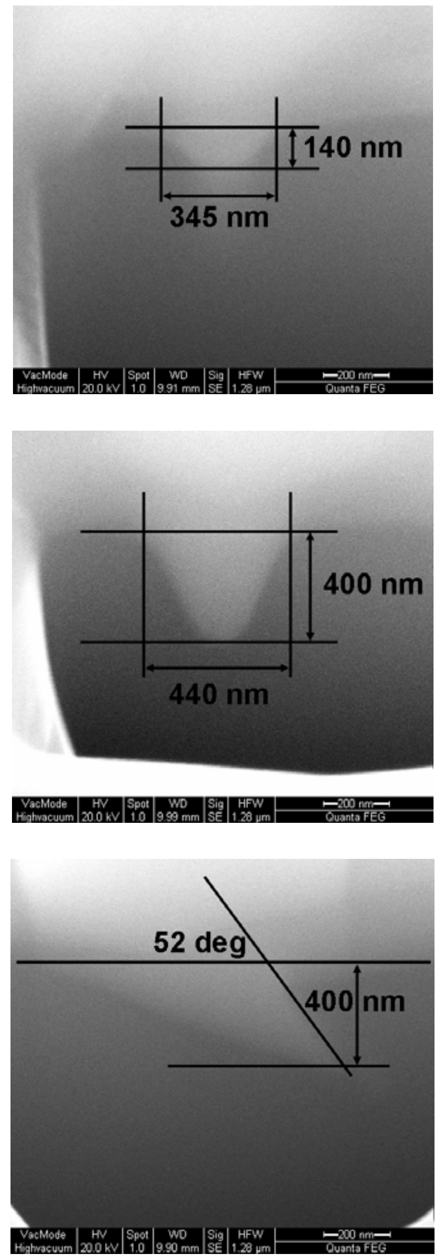

Figure 4: Lines FIB milled into Si at 52^o incidence angle either, (top) up the slope, (middle) down the slope, or (bottom) across the slope.

4 CONCLUSIONS

Nano-machining can be accomplished using focused ion beams. The geometry of the FIB milled cuts can be altered consistently with ion-solid interaction theory.

REFERENCES

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