doi:10.1017/S1431927611004247
Microsc. Microanal. 17 (Suppl 2), 2011

Experimental Observations on FIB Milling using a Custom Software Interface

N.H.M. Caldwell,* J.R. Poole, B.C. Breton, and D.M. Holburn

* Department of Engineering, University of Cambridge, Trumpington Street, Cambridge, CB2 1PZ, United Kingdom

In focused ion beam (FIB) milling, *sputtering* (the removal of material) is the desirable interaction between the ion beam and the specimen. Undesirable interactions include *redeposition* (where sputtered material condenses to the solid phase on contact with the specimen surface) and *amorphisation* (where low energy ions become implanted in the crystalline lattice.) Redeposition causes the actual milling depth to be less than desired and sloped sidewalls; amorphisation leads to defects in the surface topology of the specimen. Mathematical models such as the Yamamura theory exist to describe the dependence of the sputter yield on the angle of the incidence of the ion beam [1]. Milling formulae, such as that of Nassar and coworkers, can define the milling depth at a particular point relating it to the ion dose at the point, the specimen's atomic density, the ion beam intensity, the angle dependent sputter-yield and the ion beam dwell time [2]. The Nassar formula takes into account the action of the beam at all locations (to handle its Gaussian spread) to define the local milling depth at one point, but does not compensate for redeposition. Multiple milling passes (each a fraction of the intended depth) have been shown to mitigate deposition artifacts [3].

As part of a FIB instrument characterisation project, we developed a custom software prototype, implemented in C++, to enable an investigator to generate a suitable sequence of coordinates and dwell times to etch the desired shape. The software enables the size and location of a series of shapes to be specified, generates the minimum bounding box that encompasses all the target objects, segments the depth profile into a set of thin slices, solves the milling equation for the dwell times at each slice, and then outputs a comma-separated value (CSV) file of coordinates and dwell times. Nassar's milling formula is converted into a pixel-based and matrix format, enabling dwell times to be calculated using standard (if computationally expensive) matrix operations.

To conduct our experiments, we had access to a Carl Zeiss NTS CrossBeam® workstation equipped with EsB technology (courtesy of the Carl Zeiss NTS Cambridge R&D team). This dual-beam FIB-SEM could accept CSV files via the SmartSEM™ application to execute as milling templates, and enable the results to be viewed via its SEM beam. For experimental purposes, simple 50 x 50 pixel test squares with a pixel spacing of 90nm (square side length of 4.5μm) and a depth of 1μm were used, and comparisons were made between the standard milling approaches built-in to CrossBeam® and our implementation.

The initial experiments quickly revealed that supplying CSV files to the CrossBeam® system involved the use of a software layer that was reliant on Windows operating systems timers, which limited the shortest dwell time to 15ms with a time resolution of 1ms. (The built-in CrossBeam® milling implementations rely on hardware timers and do not have this limitation.) To offset this limitation, beam current was reduced as low as 1pA to 5pA, necessitating much longer times to complete a full milling pattern. Fig. 1 shows the results of a 5pA beam (90nm pixel size) with ten large horizontal structures along the bottom of the trench, fairly straight sidewalls (so a success in this regard) and a beveled top.

Close observation of the resulting images shows that the sidewalls parallel to the beam scan direction display much less “damage” than the sidewalls that are perpendicular to the beam scan direction. It is possible that making the beam scan direction parallel to “nearby” sidewalls might cause them to exhibit less damage. The trench base artifacts are parallel to the beam scan direction, and their formation may be a two-stage process of *genesis* where redeposited material lands on the trench floor, followed by *growth* where sputtered material from later milling passes is more likely to land on the artifact simply due to its extra height. These trench base artifacts might be mitigated if the beam scan direction for a particular layer is perpendicular to the beam scan direction of the previous layer. It is also possibly the case that the software overheads of processing pixel dwell times may be further exacerbating the generation of the trench floor artifacts.

Proceeding further with this research approach requires the removal of the dependence on Windows-based timers. An alternative to using the hardware timers would be multimedia timers which have a microsecond resolution, though to avoid jitter in the timing output, these require the executing computer to be free from interrupts and other delays. With the minimum dwell time constraint eliminated, it would be possible to use the software prototype to characterise the ion beam. Adding additional shapes to the current set (lines, rulers, squares and trapezia), increasing the speed of the matrix calculations, and enhancing the user interface would be additional improvements [4].

References

[1] Y. Yamamura et al., *Angular Dependence of Sputtering Yields of Monatomic Solids*, IPPJ-AM-26, Institute of Plasma Physics, Nagoya University, Japan, 1983.
[2] R. Nassar et al., *J. Vac. Sci. Technol. B,* 16:1 (1998) 109.
[3] M.J. Vasile et al., *J. Vac. Sci. Technol. B,* 17:6 (1999) 3085.
[4] CrossBeam® is a registered trademark and SmartSEM™ is a trademark of Carl Zeiss NTS GmbH. This research was supported by funding from Carl Zeiss SMT. The authors gratefully acknowledge the assistance of Carl Zeiss personnel, especially Daniel Aldridge, David Hubbard, and Richard Moralee.

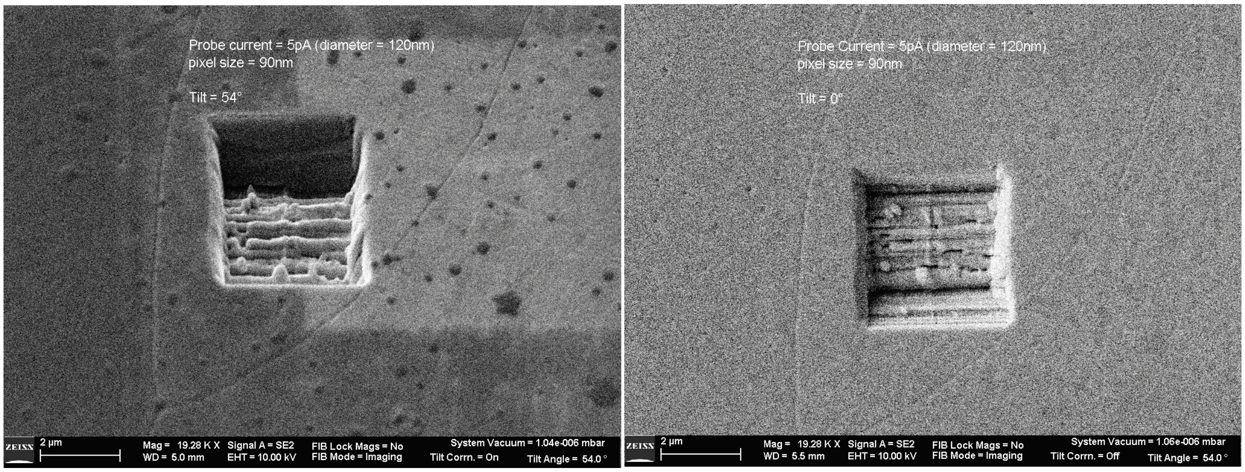

FIG. 1. SEM images of 5pA FIB test square mills using prototype software, pixel size of 90nm. Left hand micrograph at tilt of 54 degrees, right-hand micrograph at 0 degrees giving plan view.