Understanding Nanomachining in Gold Substrates

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The ability to machine materials on the nanometer scale has many applications ranging from nanoelectronics and integrated circuit editing[1] to the creation of nanopore sensors[2] and optical devices.[3] The Orion helium ion microscope, with a typical probe size of less than 1 nm, offers a new, unique method for nanofabrication at a scale currently unattainable by conventional Ga^-based focused ion beam (FIB) processing. The Orion's gas field ion source, produced with He^+, results in a smaller interaction volume near the surface and lower sputter yield as compared to heavier ions.[4] Feature sizes of 5 nm or smaller have been demonstrated in thin membranes,[2,3,5] however it remains to be seen how mill rates and attainable feature quality depend upon the film thickness and milling conditions; nor has bulk milling been studied in detail. Contrary to earlier work,[5] a recent publication indicates that backside or transmission milling in membranes with thicknesses less than the ion range is a significant factor leading to non-linearity in the mill rate for silicon nitride membranes.[6]

Here we investigate sputter yield in gold foil as a function of feature size. We have observed that surface contamination significantly affects the milling of gold. The low sputter yield with He^+ (about 2 orders of magnitude lower than with Ga^+) presumably gives contaminants time to diffuse to the milling site. Figure 1(a,b) illustrates the necessity of in-situ plasma cleaning of the chamber and sample to achieve contamination-free machining. Figure 1(c) shows that the measured sputter yield of the gold foil can change depending upon the aspect ratio of the milled features. As the aspect ratio becomes greater than 1:1, the mill rate will decrease due to increased probability of redeposition.[5] In Figure 2(a) we demonstrate how the He ion beam can be used to machine nano-to-micrometer-sized trenches, here less than 10 nm wide at a 30 nm pitch. Additionally, in Figure 2(b,c) we show that 14 nm holes can be milled through an approximately

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[1] S. Tan, *et al*., J. Vac. Sci. Technol. B **29**, 06F604-1 (2011).
[2] J. Yang, *et al*., Nanotechnology **22**, 285310, (2011).
[3] L. Scipioni, Carl Zeiss, Adv. Mat. Char.Workshop, U. Illinois, (2012).
[4] J.A. Notte, Microscopy Today 20, **16** (2012).
[5] L. Scipioni, *et al*., J. Vac. Sci. Technol. B **28**, C6P18 (2010).
[6] M.M. Marshall, J. Yang, and A.R. Hall, Scanning **34**, 101 (2012).

100 nm thick Au foil and that by reducing the film thickness, holes of half that diameter could be produced under the same conditions but with 10% of the dose. In this paper we will investigate mill rates for Au as a function of substrate thickness and compare this to ion beam scattering models to better understand the machining process in thin films and bulk substrates.

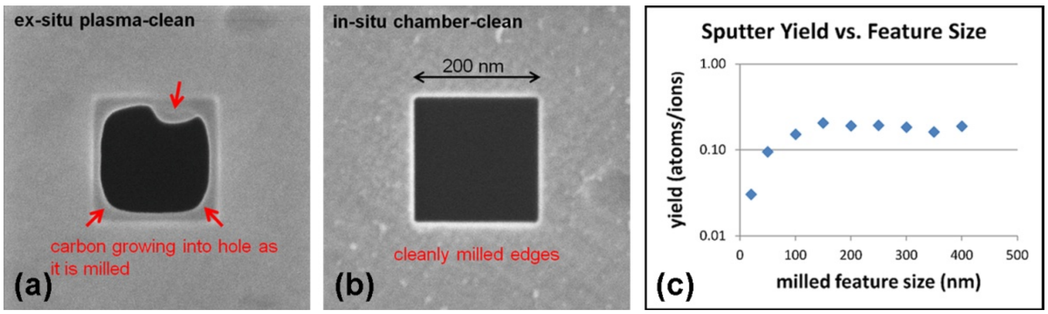

Figure 1: Helium ion micrographs of 200 nm square features milled through a ~100-nm-thick gold foil. In (a) the sample was oxygen plasma cleaned ex-situ, while in (b) the sample and chamber were oxygen plasma cleaned in-situ. Plot (c) shows the sputter yield as a function of feature size for the gold foil (calculated from mill completion time for features such as (b) in various sizes). Scan conditions: 35 keV, 4 pA, 1 µs dwell time.

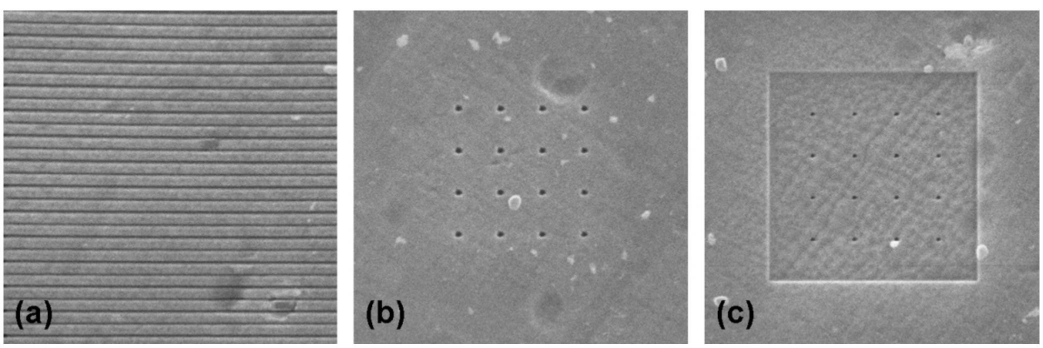

Figure 2: Helium ion micrographs patterns in a 100-nm-thick gold foil. (a) <10 nm milled lines at 30 nm pitch. A 14 nm (b) and a 7 nm (c) hole array produced with 1 second and with a 0.1 second dwell time respectively, for (c) the foil was first thinned by He ion milling over a 500 nm by 500 nm area. Beam conditions: 35 keV, 4 pA. All are 800 nm field-of-view images.