doi:10.1017/S1431927613006545
Microsc. Microanal. 19 (Suppl 2), 2013

Helium Ion Nanomachining in Membranes and Bulk Substrates

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Machining 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 helium ion microscope (HIM), with a typical probe size of less than 1 nm, offers a unique method for nanofabrication at a scale currently unattainable by conventional Ga^-based focused ion beam (FIB) processing. The HIM's gas field ion source, produced with He^+, results in a smaller interaction volume near the sample surface and lower sputter yield as compared to heavier ions [4]. While gallium atoms deposit most of their kinetic energy near the surface (making Ga^+ highly effective at bulk milling), the resulting interaction volume yields feature sizes much larger than the beam diameter. Given the long range of He^+ in most materials [5], the sputtering rate is lower than for a gallium beam; however, this means that the sample interactions don't spread the beam as quickly and sputtering events are much more likely to occur close to the beam axis (enabling smaller milling feature sizes).

Previous work has shown that some substrates such as SiO_2 and Au readily mill under the beam while other substrates such as Si and SiC exhibit a drastically different "swelling" behavior under high irradiation dose as shown in Fig. 1(a) [6]. HIM-machined feature sizes of 5 nm or smaller have been demonstrated in thin membranes [2,3,7], 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 [7], 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 [8].

As with any FIB technique, there are trade-offs between probe size and current, i.e., machining accuracy and minimizing the pattern write time and/or drift. It is also important to use the minimum dose necessary to achieve the desired result, thereby producing the smallest features with the least substrate damage. 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(b,c) illustrates the necessity of *in-situ* plasma cleaning of the chamber and sample to achieve contamination-free machining. 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 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 milling of Au and other substrates as a function of thickness and beam parameters and compare this to ion beam scattering models [5] to better understand the machining process in thin films and bulk substrates.

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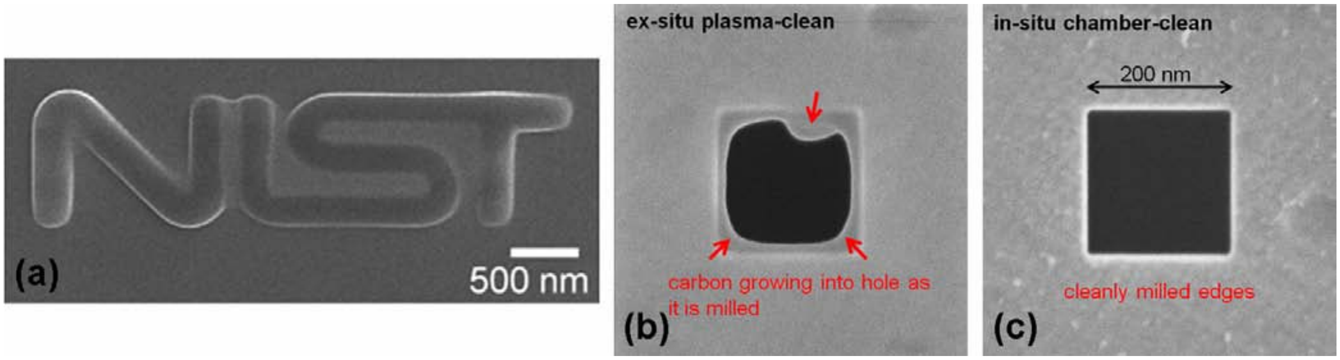

Figure 1. Helium ion micrographs of (a) helium swelling in a silicon substrate (b,c) 200 nm square features milled through a ~100-nm-thick gold foil. In (b) the sample was oxygen plasma cleaned ex-situ, while in (c) the sample and chamber were oxygen plasma cleaned in-situ. Scan conditions: 35 keV, 4 pA, 1 µs dwell time.

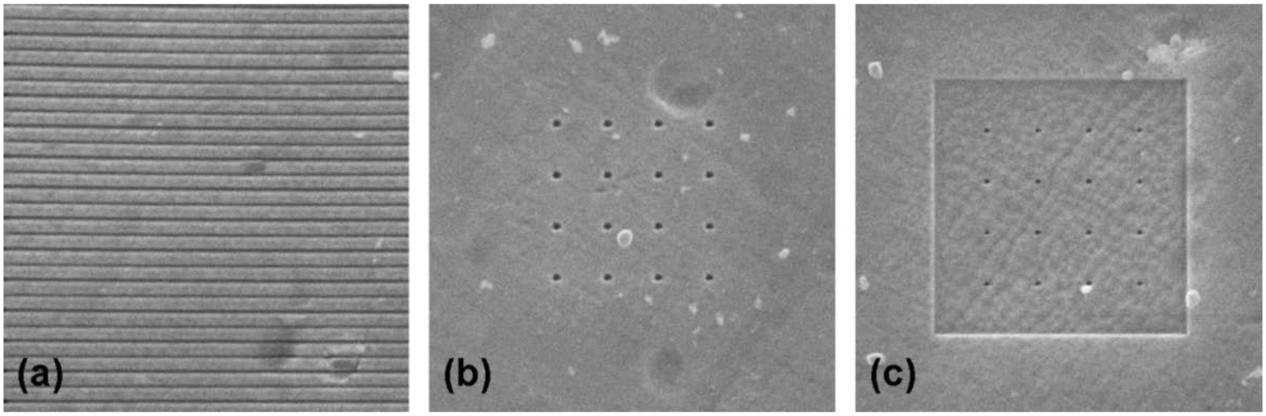

Figure 2. Helium ion micrographs patterns in a 100-nm-thick gold foil. (a) <10 nm milled lines at 30 nm pitch. A 14 nm (b) and a 7 nm (c) hole array produced with 1 second and with a 0.1 second dwell time respectively, for (c) the foil was first thinned by He ion milling over a 500 nm by 500 nm area.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