Understanding Focused Helium Ion Beam Nanomachining of Membranes and Bulk Substrates

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Focused helium ion beam has characteristically low sputter yield and smaller interaction volume near the surface as compared to focused gallium ion beam.[1] As a result, fabricated nanometer-scale structures with feature sizes of 5 nm or smaller have been demonstrated in thin membranes.[2,3,4] Yet it remains to be seen how mill rates and feature quality depend on the film thickness (up to bulk thickness) and on milling conditions. This work is aimed at quantifying sputter yield and/or surface modification of integrated circuit and device-relevant materials, such as Au, SiN, SiC, Si, a-Si, SiO_2 and quartz, through modeling and experimental analysis in order to achieve reliable, high-resolution, and efficient nanomachining.

Fig. 1 shows an example of a 200 nm box milled in 100 nm gold foil compared to a 200 nm box milled in a bulk substrate with comparable dose. As can be seen, achieving notable results in bulk substrates is not easy due to the accumulation of dislocations and to the damage caused by the trapped helium to the surrounding and underlying areas. To better understand this, SRIM models[5] and milling experiments in thin films and bulk substrates were performed. It was found that the experimentally determined sputter yield for a 100 nm gold foil was significantly higher than theoretical calculations, presumably due to transmission milling,[6] which is not accounted for in the SRIM model. Very fine features in thin films, as in Fig. 1c, can be milled at lower beam energies due the fact that the focused He beam does not spread significantly in the first 20 nm of thickness (see Fig. 2a). An enhanced sputter yield was also observed in gold for 20 keV beam energy compared to 30 keV. This is attributed to the difference in ion range as shown in the model beam interaction profiles in Fig. 2. Furthermore, the theoretical sputter yield (for front-side milling only) was examined as a function of beam energy for different substrate thicknesses. The results shown in Fig. 3 indicate that maximum sputter yield occurs at around 5 to 7 keV ion beam landing energy for all thicknesses. Nanomachining at the optimal sputter yield would result in lower dose requirements and potentially cause less damage.

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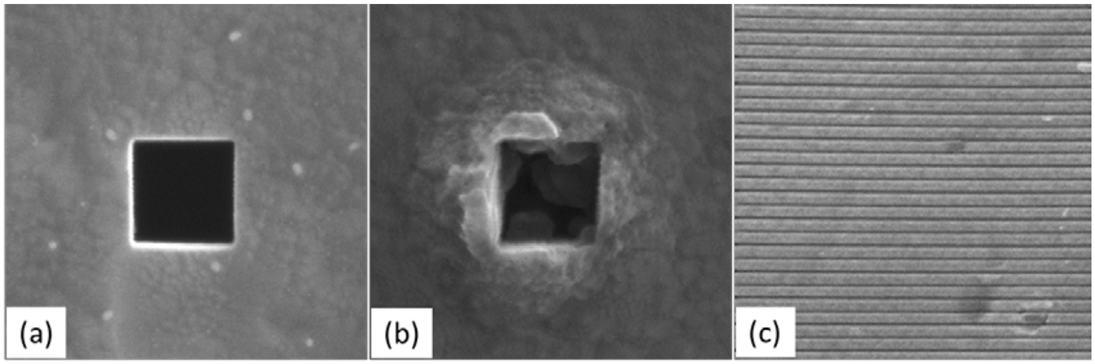

Figure 1. Helium ion micrographs of helium-milled features in gold: (a) 200 nm square milled through a ~100-nm-thick gold foil and (b) ~400-nm-thick gold; (c) <10 nm wide lines milled at 30 nm pitch on ~100-nm-thick gold foil.

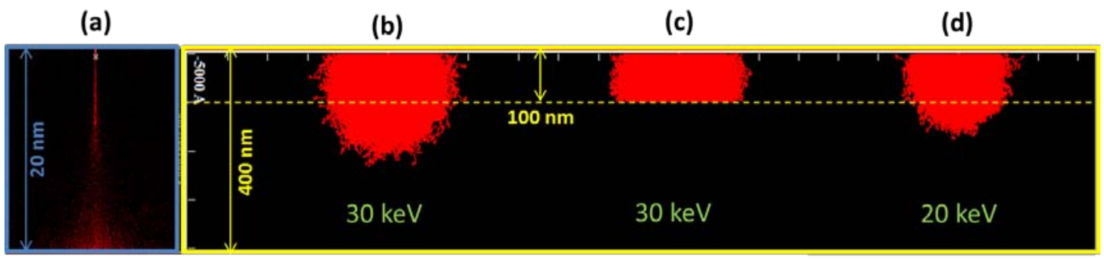

Figure 2. SRIM Ion Trajectory Images generated using 10,000 incident ions. Fine features in 20 nm films can be achieved at 30 keV because the beam (a) is very narrow at that range. At 30 keV there is significant transmission milling for films less than 100 nm (c). Damage to surrounding areas can be reduced by using lower beam energy of 20 keV (d) with a smaller range as compared to (b).

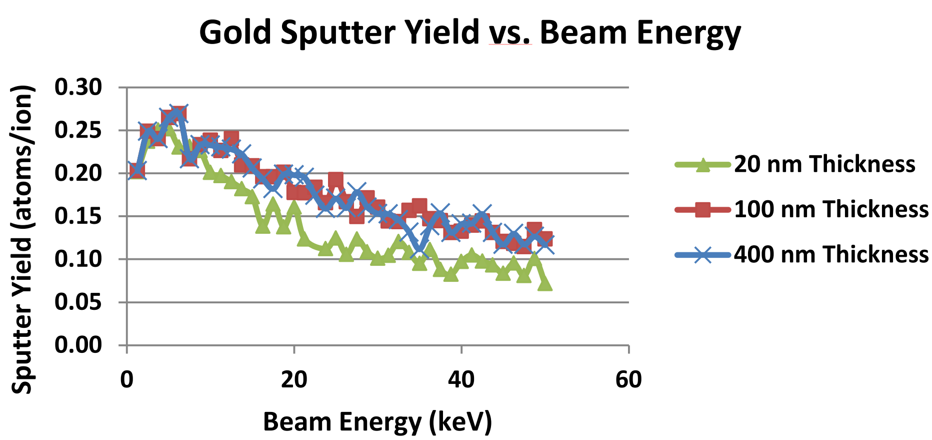

Figure 3. Theoretical sputter yield as a function of beam energy for various thicknesses of gold. For all substrate thicknesses there is an upward trend in sputter yield as beam energy decreases, peaking between 5 and 7 keV. Since the ion range in Au is less than 100 nm, the behaviors of the 100 nm and 400 nm films are similar. The 20 nm foil is thinner than the range of ions for all energies greater than ~6 keV and has a lower sputter yield due to the increased number of transmitted ions (transmission milling is neglected in this model).