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Focused Ion Beam Sculpting Curved Shapes

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A focused ion beam (FIB) is used to accurately sculpt predetermined micron-scale, curved shapes in a number of solids. Using a digitally scanned ion beam system, various features are sputtered including hemispheres and sine waves having dimensions from 1-50 µm. Ion sculpting is accomplished by changing pixel dwell time within individual boustrophedonic scans. The pixel dwell times used to sculpt a given shape are determined prior to milling and account for the material-specific, angle-dependent sputter yield, $Y(\theta)$, as well as the amount of beam overlap in adjacent pixels. A number of target materials, including C, Au and Si, are accurately sculpted using this method. For several target materials, the curved feature shape closely matches the intended shape with milled feature depths within 5% of intended values.

Results and Discussion

There have been few attempts at 3-dimensional ion milling or sculpting for the purpose of controlling feature shape [1-5]. The method [1-3] we employ involves numerical determination of the dose required per pixel to attain a user-specified shape. Of note, the method accounts for the sputter yield variation with incidence angle ($Y(\theta)$) when solving for the required dose. For sculpting, an initially planar sample is fixed with the angle of ion incidence set at 0^o (normal incidence), and an area is outlined in plan view. The dose required per pixel is then partitioned according to the number of user-specified scan repeats.

The angular dependence of yield is determined experimentally prior to sculpting. We have completed this determination for a number of materials and find that the yield depends on angle similar to the formulation put forth by Yamamura [6]. In general, the yield depends on the incident energy, E, and angle of incidence, θ, as

$$Y(E,\theta) = Y(E)\, t^{f} \exp[-\Sigma(t-1)] \quad \text{with } t = 1/\cos\theta$$

where f and Σ are parameters determined from a fit of the experimental data.

Figure 1 plots the experimentally-determined yield for Si versus angle. This data was obtained by tilting a silicon specimen to different angles of incidence prior to separate mill steps. The line shown in this plot is a fit using the Yamamura formulation with $f = 2.43$ and $\Sigma = 0.43$. For Si the yield at 0^o (normal incidence) is measured to be 1.94 ± 0.06. Additional values of yield, f and Σ are listed for C and Au in Table 1.

Using the values listed in Table 1 a number of curved shaped features were ion beam sculpted. Figure 2 shows an example of a sinusoidal wave and a hemisphere sputtered into carbon. The maximum depth of these features comes close to the targeted values although consistently 10-15%

shallow for C. We believe that the deposition of ejected carbon is responsible for this slight error. This appears to be a significant effect when milling Si and C, but not Au.

References

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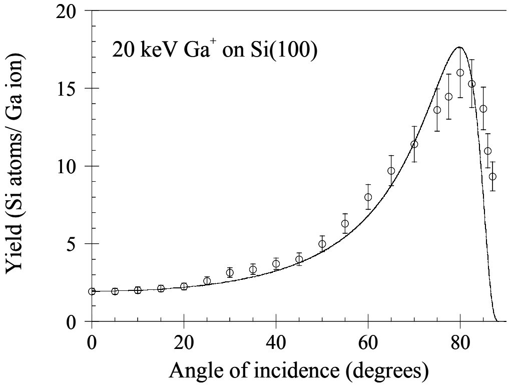

Fig. 1. Plot of Y(θ) for Ga bombardment of Si(100). The solid line represents a fit using the Yamamura formulation.

Target	Density, 10^{22}at/μm^3	$Y_{exp}(0^o)$ (std.dev.), at/ion	f_{exp}	Σ_{exp}
Si(100)	5.00	1.94 (0.06)	2.43	0.43
C(100)	17.6	2.00 (0.08)	0.81	0.047
Au(100)	5.90	8.61 (0.25)	2.36	0.875

Table 1. Experimentally determined yield at 0^o and fitting parameters (f_{exp}, Σ_{exp}) for various target materials. The parameters listed are characteristic of 20 keV Ga$^+$ ion beam bombardment to high doses (>10^{19} ions/cm^2).

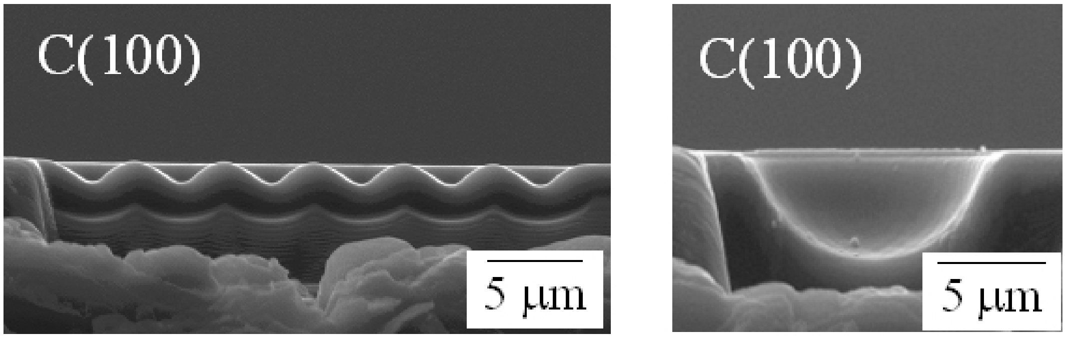

Fig. 2. Features sculpted in diamond using FIB sputtering.