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Sputtering Erosion Measurement on Boron Nitride as a Hall Thruster Material

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September 2002

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Abstract

The durability of a high-powered Hall thruster may be limited by the sputter erosion resistance of its components. During normal operation, a small fraction of the accelerated ions will impact the interior of the main discharge channel, causing its gradual erosion. A laboratory experiment was conducted to simulate the sputter erosion of a Hall thruster. Tests of sputter etch rate were carried out using 300 to 1000 eV Xenon ions impinging on boron nitride substrates with angles of attack ranging from 30 to 75 degrees from horizontal. The erosion rates varied from 3.41 to 14.37 Angstroms/[sec (mA/cm^2)] and were found to depend on the ion energy and angle of attack, which is consistent with the behavior of other materials.

1. Materials and Methods

Before the start of the experiment, each 1-inch diameter boron nitride sample supplied by the On-Board Propulsion branch was polished to insure a smooth surface for accurate surface profiling. After polishing, half of each sample to be placed into the Ion Tech Dual Beam II was masked so that an erosion step would be produced. This mask consisted of a 3-layer shim to prevent thermal distortion and thus assure that the thinnest shim remained in intimate contact with the boron nitride so that a clean, abrupt erosion step would form. The mounting fixture used in this experiment also contained a probe to determine the current density at the sample position at the beginning and end of each trial. When the current density was measured, the sample faced the bottom of the dual beam and the probe was moved to the exact location where the sample had been, as shown in Figure 1.

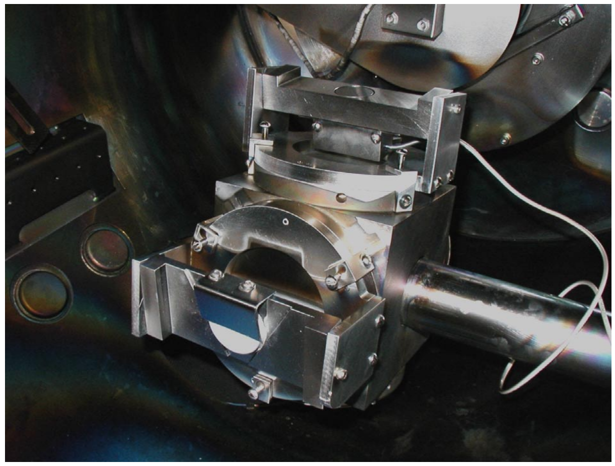

Figure 1: The entire mounting fixture including the masked sample positioned to ion exposure, as well as the current probe, which is facing upward.

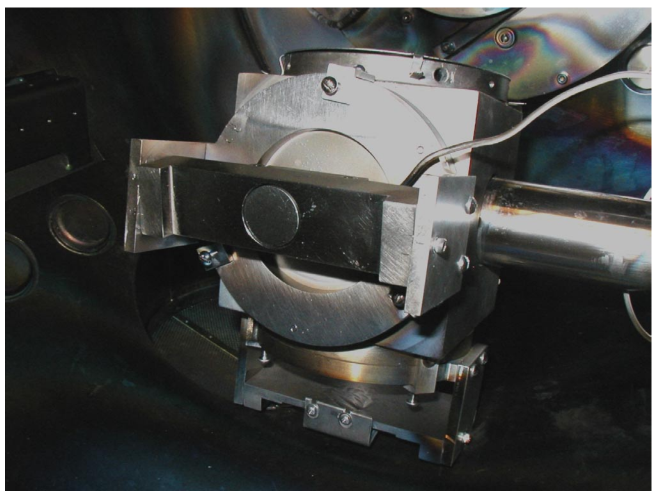

Figure 2: The current probe placed in position to measure current density.

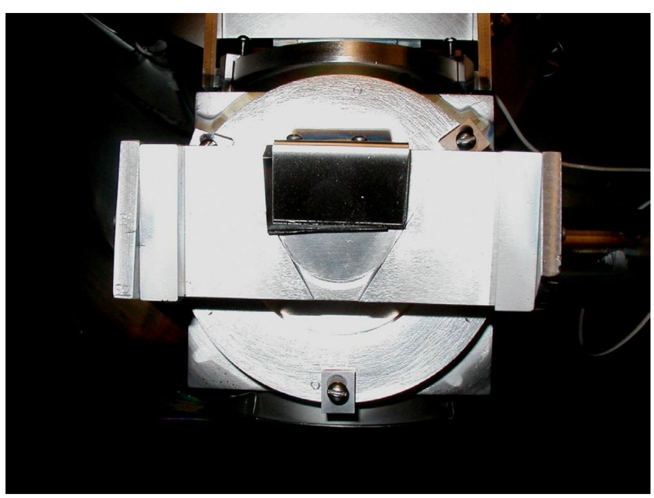

Figure 3: Close-up of the apparatus used to mount and mask the sample at the same time.

The current probe was biased –15 volts relative to ground potential to eliminate the collection of secondary electrons. The mounting fixture, shown in the three figures above, has two targets for the beam that are adjustable to any required angle. At the start of the test run, the current probe target was exposed to the beam. Then, in order to sputter etch the boron nitride sample, the entire mounting apparatus was rotated 90 degrees so that the sample was precisely where the current probe had been previously. Immediately after the sputter etching was completed, the current probe was again moved into the original position for the final current measurement.

Each boron nitride sample was exposed to different xenon ion energies (300, 600, and 1000 eV) as well as different angles (30, 50, and 75 degrees) with respect to the 5-cm diameter Kaufmann type ion source, shown in Figure 4. The samples were profiled for at least two and a half hours for higher beam energies and three to four hours for the 300 eV trials. During each run, the beam current was kept constant to insure constant sputter etching conditions.

Figure 4: Close-up of ion source including accelerator grids and neutralizer in Dual Beam II.

2.1 Data Analysis and Discussion

Following the test run, each sample's profile was taken by a Dektak IIA Profilometer at ten different points to determine the magnitude of erosion from exposure in comparison to that of the masked portion of the sample. These ten points were distributed evenly across the same area on the sample where the ion beam was directed at the current probe. Key information for each test run is presented in the table below.

Table 1: Data from each test run

Angle	75 degrees			50 degrees			30 degrees		
Energy (eV)	1000	600	300	1000	600	300	1000	600	300
Starting current (mA)	6.8	6.7	3	6.6	6.2	2.4	2.5	3.9	1.4
Ending current (mA)	8	6.2	2.6	8.5	6.1	2.4	2.8	2.5	1.2
Average Erosion Height (A)	136056	72063	26178	141075	67840	20045	78137	46950	21693
Prob. error erosion height (A)	5752	4705	4097	14327	4368	4914	5561	8865	1291
Run time (s)	10800	10020	13800	10800	11100	12600	10500	9000	14400
Erosion rate $\left(\frac{A \cdot cm^2}{\sec \cdot mA}\right)$	8.79	5.76	3.50	8.90	5.11	3.41	14.37	8.34	5.93
Total error, erosion rate	0.53	0.45	0.58	0.97	0.40	0.86	1.39	1.64	0.77

From average erosion depth, the erosion rate E per milliamp was found from the following equation:

$$E = \frac{\pi H D^2}{2t\left(j_{p_1} + j_{p_2}\right)} \qquad (1)$$

where H is the mean average erosion height in Angstroms, D is the diameter of the current probe (2.54 cm), t is the test run duration in seconds, and j_{p1} and j_{p2} are the currents in milliamps at the beginning and end of each test run, respectively. Including these two parameters normalizes the erosion rate to a current density of 1 mA/cm^2. A small correction factor (<2%) in the calculation of the surface area was used to account for ions hitting the leading edge of the current probe.

2.2 Calculation of Error in Erosion Rate

The error values shown in both Table 1 and Figures 6 and 7 are probable errors that were determined by using propagation of errors given by the following equation:

$$E + \delta E = E \pm \left(\sum_{x_i} \left(\frac{\partial E}{\partial x_i} \delta x_i \right)^2 \right)^{\frac{1}{2}} \qquad (2)$$

Here x_i is any one of the following variables in Equation 1: average height, diameter, time, and current density while δx_i is the probable error of each variable. The probable error in the time variable was taken to be ±5 seconds, while the uncertainty of the diameter variable was taken to be ±0.05 cm. Currents were measured to an accuracy of 0.1 mA, while the probable error, P, for the step height was determined by the equation below:

$$P = 0.6745\sigma \qquad (3)$$

where σ is the standard deviation of the step height measurements taken by the profilometer. The largest source of error in this experiment is the variance of the profilometer readings for the step height. A variety of factors might have caused this, such as the ion beam not being centered perfectly or the test runs not being long enough to allow for a more uniform distribution of ions to the surface of the sample.

2.3 Data Trends

From Figure 6 below, is it evident that the erosion rates generally increase with ion energy. For each angle orientation, the erosion rate increased with the ion energy. The definition for angle orientation θ is shown in Figure 5.

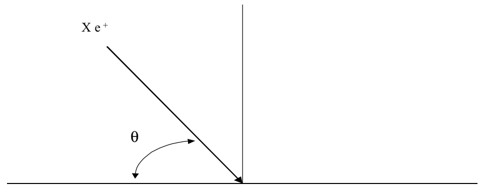

Figure 5: Definition for θ.

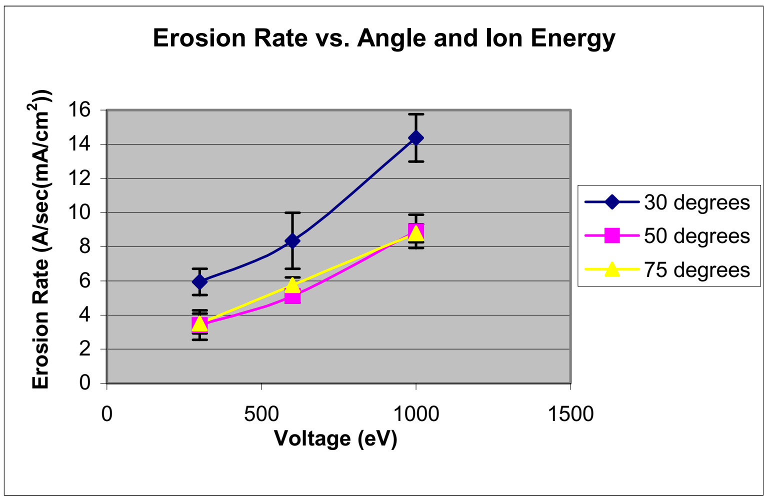

Figure 6: Trend between erosion rate, angle, and ion energy.

One would expect erosion rate to be dependent on the sample's orientation to the ion source. The graph shown in Figure 6 suggests that the erosion rate generally decreases; the 50-degree and 75-degree trials are lower than that of the 30-degree trials.

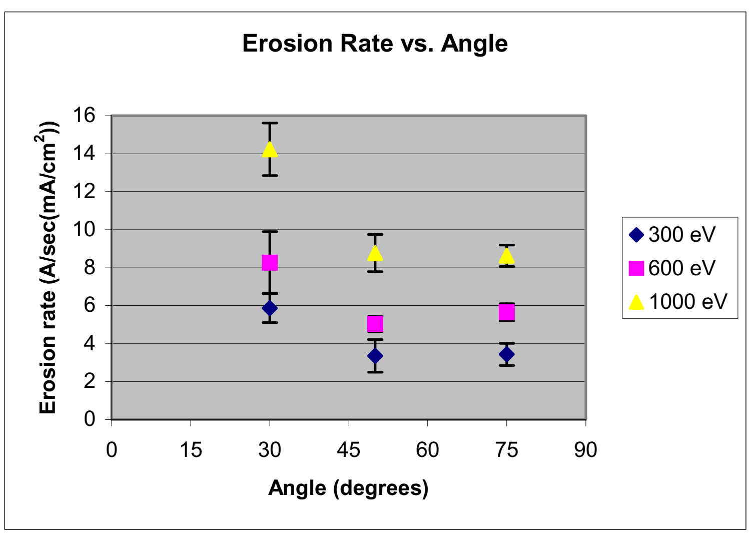

Figure 7: Trend between erosion rate and angle with respect to ion source.

It is unclear that the 75-degree erosion rates are above those of the 50-degree erosion rates. A quick look at the data presented in Table 1 reveals that the calculated erosion rates for these two data sets are reasonably close for all beam energies, and overlap of probable errors prevents definitive discrimination.

This data set does reflect similar data of other materials. It is known that some materials exhibit a maximum sputter yield at an angle θ_{max} other than perpendicular to the ion source. In Figure 8, notice the peak present in the nickel and molybdenum curves. The value of θ_{max} can range anywhere from approximately 35 to 50 degrees for any given material. Therefore, the 30-degree orientation may have been near θ_{max} for boron nitride, thus explaining the high erosion rates at this orientation.

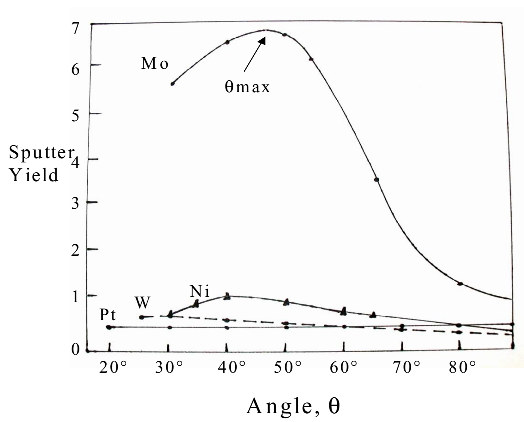

Figure 8: Sputter Yield versus Angle with respect to ion source.

3. Conclusions

From the analysis presented above, it is reasonable to conclude that the data collected are representative of what would be found with other materials. It has been shown in Figure 6 that erosion rates increase as expected with ion energy. However, the 30-degree orientation yields the highest erosion rates because this particular angle may be closest to the θ_{max} for boron nitride.

In order to obtain more accurate results in future experiments of this type, it would be essential to reduce the fractional error due to the variance in step height measurements. Making use of longer run times and obtaining a greater number of profilometer readings across each sample surface should also decrease the total calculated error in the erosion rates. Also, conducting the test at a wider range of angles would help in estimating erosion rates for any orientation.

4. Reference

R. Jankovsky, D. Jacobson, L. Pinero, C. Sarmiento, D. Manzella, R. Hofer, and P. Peterson, "NASA's Hall Thruster Program 2002," AIAA–2002–3675, 38th AIAA Joint Propulsion Conference, Indianapolis, Indiana, July 7–10, 2002.

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