Low Energy Xenon Ion Sputtering Yield Measurements*#

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Low energy (<500 eV) xenon ion sputtering yields were measured with a tantalum target. The sputtering was carried out in a UHV chamber. The targets were bombarded with a xenon ion beam generated by an ion gun capable of producing a beam current of approximately 1.0 µA. The sputtered atoms were captured on a semi-cylindrical aluminum collector strip. The thin film on the collector strip was analyzed with a Rutherford Backscattering Spectrometer. The sputtering yield was obtained from the atomic density and the thickness of the sputtered film. The measured sputtering yields were compared to those found in literature.

Introduction

Sputtering, a process by which a target atom is removed by impinging ions, has been observed in electric propulsion thrusters as well in fusion devices such as the Tokamaks. Even though sputtering has been studied since the early sixties, the need still exists for accurate sputtering yield data, especially for heavy ions at low energies (<500 eV)[1,2]. Most work to date has been performed to fit the requirements of fusion devices, that is with light ions [3].

In ion thrusters, sputtering occurs from surfaces which are at cathode-potential in the discharge chamber. One of these surfaces where xenon ions impinge upon is the upstream-side of the screen grid, which is typically made of molybdenum. The ion energy in the discharge

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chamber is close to the discharge voltage of approximately 26 V. This level of ion energy is believed to be below the sputtering threshold energy of a xenon-molybdenum sytem [4]. Therefore, it can be concluded that doubly ionized ions do most of the erosion to the screen grid because these ions have twice the energy of the singly ionized ions. The downstream side of the accelerator grid undergoes sputtering by charge-exchange ions. The energy of the charge-exchange ions can be as high as the accelerator voltage, which generally is between 200 to 300 V. The range between the discharge and accelerator voltages define the ion energy range of interest in ion thrusters. The characteristics of NASA Solar Electric Propulsion Technology Readiness Program (NSTAR) thruster, the latest generation of NASA ion thrusters, are described in Ref. [5]. The energy of ions in Hall thrusters extends the range of interest to above 500 eV.

The compilation of sputtering yields found in literature for a molybdenum-xenon system is shown in Fig. 1. Even though quite a number of measurements of sputtering yields of xenon-molybdenum have been performed, it is evident that the spread in the data is significant. The data of Ref. [19] exceeds measured value of all the other measurements. These measurements were obtained by using a thin film as the target. It is not known if this may be the reason for the discrepancy. It is apparent that as the ion energy decreases below 200 eV, the spread in the data becomes larger. This trend can be attributed to the increasing difficulty of sputtering yield measurements with decreasing ion energy [1].

There are numerous difficulties encountered with low energy sputtering yield measurements [1,2]. Early-sputtering measurements were made in plasmas. These conditions offered certain advantages as well as disadvantages compared to later measurements performed with ion beams in high vacuum chambers. A necessary condition for obtaining reliable sputtering data is that ion bombardment is performed with a well-defined ion beam both with regard to ion species and energy. In plasma experiments these requirements may present some difficulties. Most important is to eliminate the effects on sputtering due to background gasses (residual gasses under no load conditions) in the vacuum facility, as well as contaminant gasses in the propellant. This requirement is difficult to quantify because the effects of chemisorbed gasses on sputtering rates are difficult to characterize. The sticking coefficients and binding energies of these background gasses are not generally available [1]. The effects of background gasses in vacuum facilities have been observed in ion thruster lifetests [6]. The effect can be explained by the chemisorption of facility background gasses on the thruster ion optics and thus altering the sputtering yield of the target material itself [7].

The preparation of the target surface, such as the removal of stable oxides formed on the target and surface roughness, are also of importance [3,8]. Eckstein claims that agreement of experimental data can be as good as a few percent but deviations may be encountered up to a factor of about two, whereas, discrepancies near the threshold energy may be even larger [3].

The problem is aggravated by the fact that there is also a lack of reliable theoretical models for low energy ion sputtering especially near threshold energy values [2]. The problems encountered with sputtering models arethe lack of reliable measured sputtering threshold energy data that serve as a benchmark for these analytical models and the lack of consistent models. There are as many as 12 different formulations for the threshold energy providing a large range of values (28-252 eV) for molybdenum-xenon [9]. Some analytical models require threshold energies of up to 64 eV to fit the measured sputtering data for xenon-molybdenum systems down to 100 eV. Experience with ion thruster erosion rates have indicated that the xenon-molybdenum threshold values must be considerably less than 64 eV. There have been recent measurements with Secondary Neutral Mass Spectrometry indicating sputtering threshold energies may be as low as approximately 10 eV. Wilhelm [10] has derived a model from quantum mechanical considerations, which offers some promise for calculating sputtering yields near threshold energies. Presently Ray is applying molecular dynamics code to formulate a model for low energy ion sputtering [11].

Many different techniques have been employed in measuring the mass loss in sputtering yield measurements [12]. The most frequently used technique utilizes a scale to measure the weight lost during sputtering process. However, at low energies the weight loss is so small that more sensitive measurement techniques become necessary.

This work is essentially the continuation of a project begun at Tuskegee University. That project entailed the measurement of sputtering yields of materials of interest to ion thrusters and electric propulsion in general [13]. The sputtering yields of tantalum were measured with 100 and 500 eV xenon ions.

Experimental Apparatus and Procedure

The sputtering apparatus used in this work was the same as utilized by Tuskegee University and is described in Ref. [13]. The schematic of the apparatus is shown in Fig. 2. It consisted of a 22.5 cm diameter spherical vacuum chamber, which was evacuated by a 170-liter/sec turbomolecular pump. The pump was capable of providing a no load pressure of approximately $2x10^{-9}$ Torr after chamber preheat procedure. A hot cathode filament ionization gauge monitored the pressure inside the chamber. High purity 99.9995% xenon was used for the tests.

The ion beam was generated by an ion gun capable of generating approximately 1.0 μA. The ion beam had the capability to be focused on the target to approximately 1.0 mm diameter, however, the exact beam diameter could not be accurately predetermined. It could be measured after the test from the mark left on the target.

The target-collector assembly was mounted on a XYZθ actuator for precise positioning with respect to the ion gun. The target was placed 2.0 cm from exit plane of the ion gun.

The target was mounted on a target-collector assembly shown in Fig. 3. The sputtered atoms from the target were collected on a thin, 0.50 cm wide aluminum foil. The foil was attached to semi-cylindrical collector backing plate. The center of the target was 1.5 cm radius from collector foil. The ion beam entered the target-collector assembly through a 0.5 cm diameter hole.

The tantalum target was machined from a rod with a 1. 25cm diameter and cut to a length of .62 cm. The target surface was hand polished to remove any surface contamination. Finally it was cleaned in an ultrasonic cleaner. The ion beam impinging on the target, pressure in the vacuum chamber and the ion energy were recorded on a computerized data acquisition system.

The sputtering was stopped after a sufficiently thick tantalum layer was deposited on the aluminum foil. The thickness of the layer is more or less determined by the requirements of the Rutherford Backscattering Spectrometer (RBS). The RBS is a very sensitive technique requiring only one or two monolayers for the desired analysis [3,12]. However, such a thin layer could lead to erroneous results if the sticking coefficient is not close to 1.0 during the initial stages of deposition. Once the first mono-layer is deposited the sticking coefficient approaches the value of one [14]. The sputtering time was extended long enough to insure a sufficiently thick coating and avoid the issue of unknown sticking coefficients at the beginning of the deposition process.

A thorough description of the RBS technique is found in Ref. [13]. In the RBS analysis 1 MeV helium ions were used to probe the deposited metal on the aluminum foil. A solid-state detector detected the backscattered ions at 165° to the direction of the helium ion beam. From the RBS analysis the product of the atomic density and thickness of the collected film was obtained. The differential sputtering yield Y(θ) is obtained:

$$Y(\theta)=(R^2Nt(\theta)q)/IT \qquad (1)$$

Where: N = atomic density ($atoms/cm^3$)
R = radius of the collector strip (cm)
t(θ) = thickness of the sputtered film (cm)
q = electric charge (C/ion)
I = xenon beam current (A)
T = total sputtering time (s)
θ = scattering angle (degrees)

To simulate the under cosine character of the angular distribution, the following function was used:

$$f(\theta) = A_1\cos\theta + \ldots A_4\cos^4\theta \qquad (2)$$

The total sputtering yield is obtained by the following integral:

$$Y_{Total} = \int f(\theta)2\pi \sin\theta d\theta \qquad (3)$$

$$= 2\pi (A_1/2 + A_2/3 + A_3/4 + A_4/5) \qquad (4)$$

Results and Discussion

The RBS analysis was performed at the Pacific Northwest National Laboratory. The polar plots of the differential sputtering yield of tantalum at 100 and 500 eV are shown in Fig. 4 as well as the resulting total sputtering yield. The data indicates that the sputtered atoms of tantalum at 100 and 500 eV have under-cosine distributions. Comparison of the 100 and 500 eV data shows that the sputtered atoms are ejected at a greater oblique angle at lower ion energies. Measurements on both sides of the collector generally indicated that the lobes are symmetrical. Measurements of sputtered particles at ion energies of > 1000 eV have generally an over-cosine distribution [15].

The measured sputtering yields of tantalum from this study and others found in the literature are shown in Fig. 5. The 500 eV data point shows excellent agreement with Refs. [18,21]. The 100 eV point falls somewhat above the those data. There are less sputtering yields found in the literature for xenon-tantalum than for xenon-molybdenum.

There has been some aspersion cast upon of the early work of Wehner and Rosenberg. The claim is that background gasses affected their data, therefore, measuring a lower sputtering yield [16,17]. It should be pointed out that Wehner was well aware of the possible effect on sputtering yields due to background gasses. Wehner's lack of high vacuum in his tests may have made up by higher ion beam density than in those experiments using UHV and smaller current densities. Shea's contention that Wehner's data be "adjusted" by a factor of up to 2 for various metals at all ion energies is difficult to accept. Any "correction" factor would have to be dependent on the ion energy. And there is no experimental data to support such a proposition. The data in Fig. 5 seems to indicate that Wehner's data appears compatible made in this study as well with other measurements made under high vacuum conditions.

Conclusions

Xenon-tantalum sputtering yields were measured at 100 and 500 eV. The measured yields agreed well with the data found in the literature. The sputtering yield measurement technique utilized a UHV chamber, an ion gun to obtain a thin film of the target material and Rutherford Backscattering Spectrometer (RBS) to analyze the film. This technique appears to offer relatively accurate means of measuring sputtering yields below 100 eV. Extreme care will have to be exercised to assure that background gasses of the facility do not interfere with the measurements.

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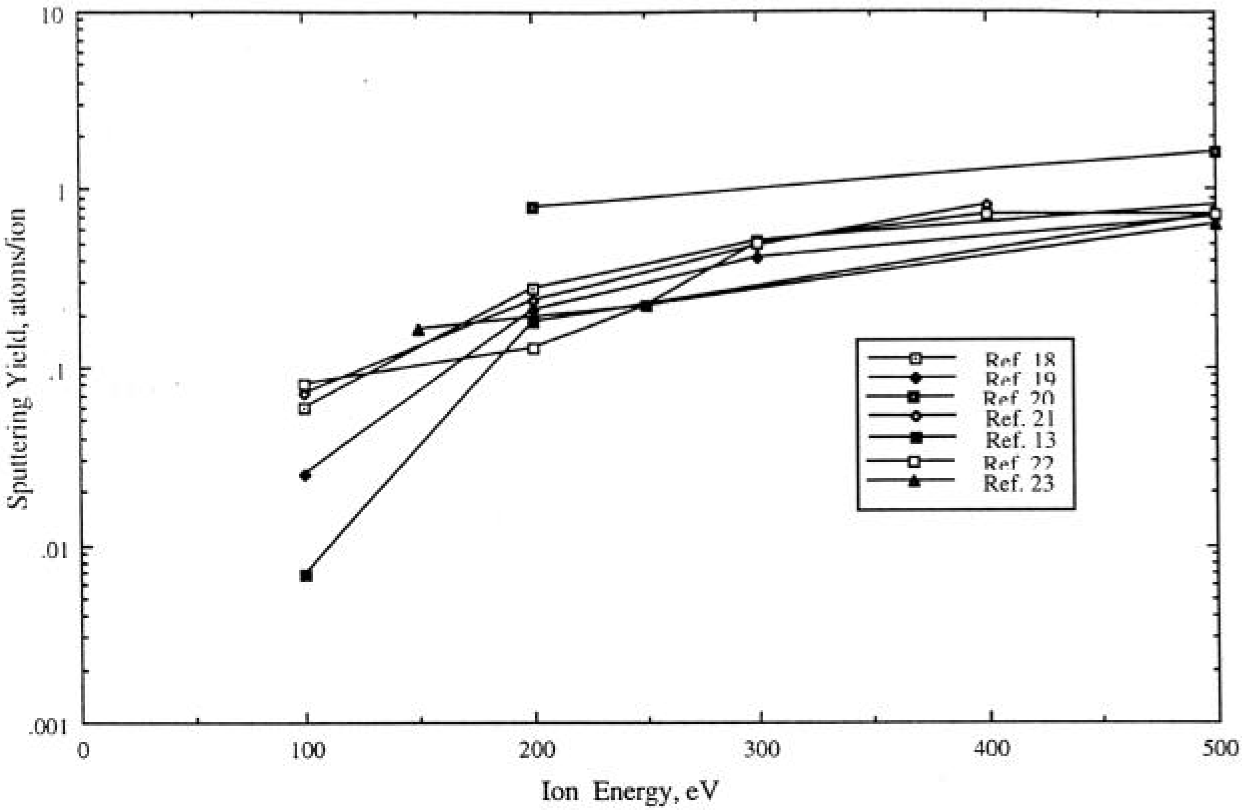

Fig. 1. Compilation of sputtering yields of xenon-molybdenum.

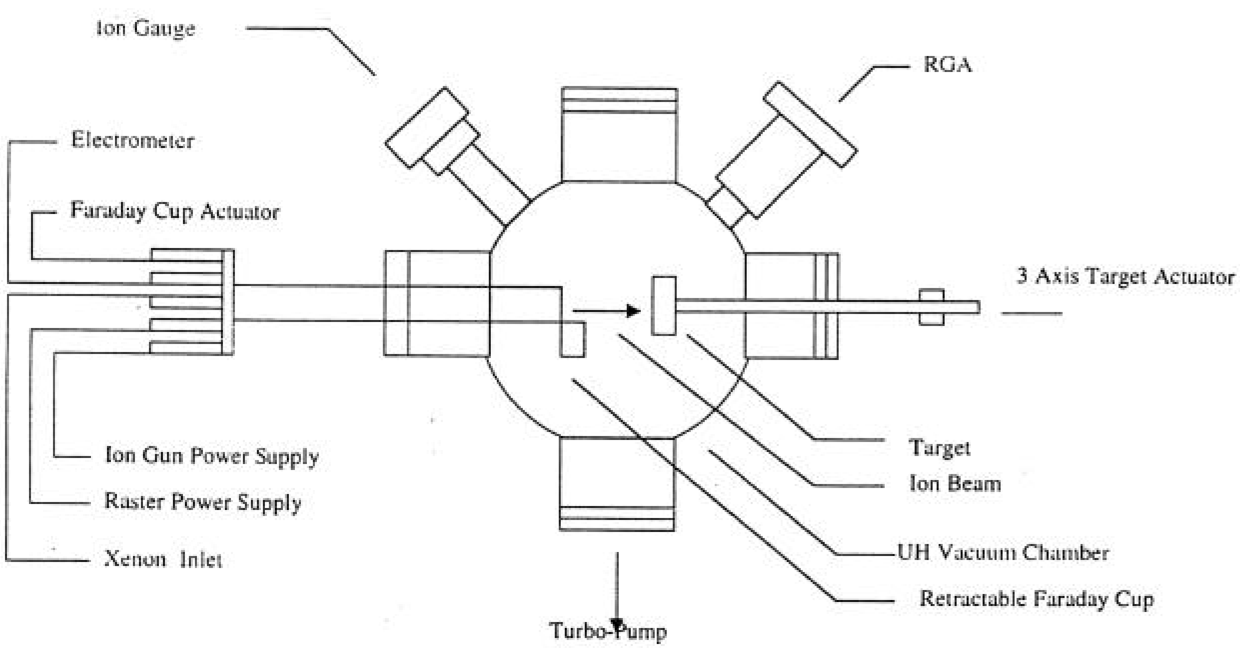

Fig. 2. Schematic of low energy ion sputtering yield measurement apparatus.

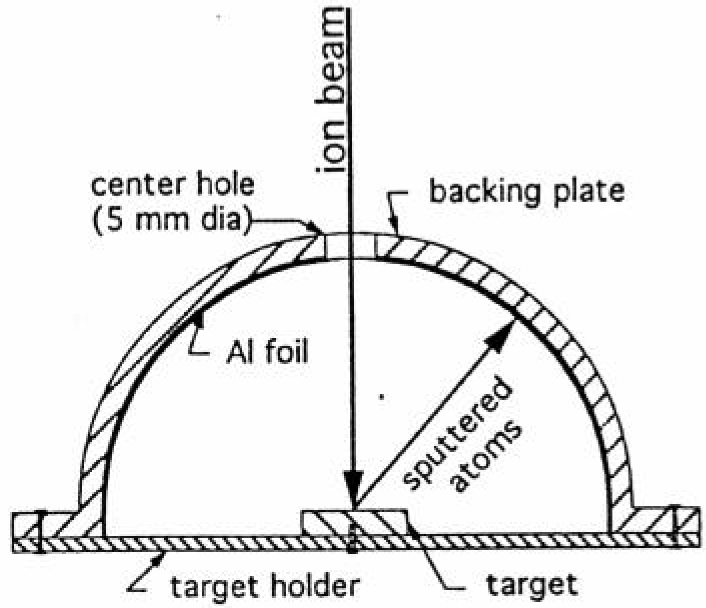

Fig. 3. Schematic of target-collector assembly. (Ref. 13)

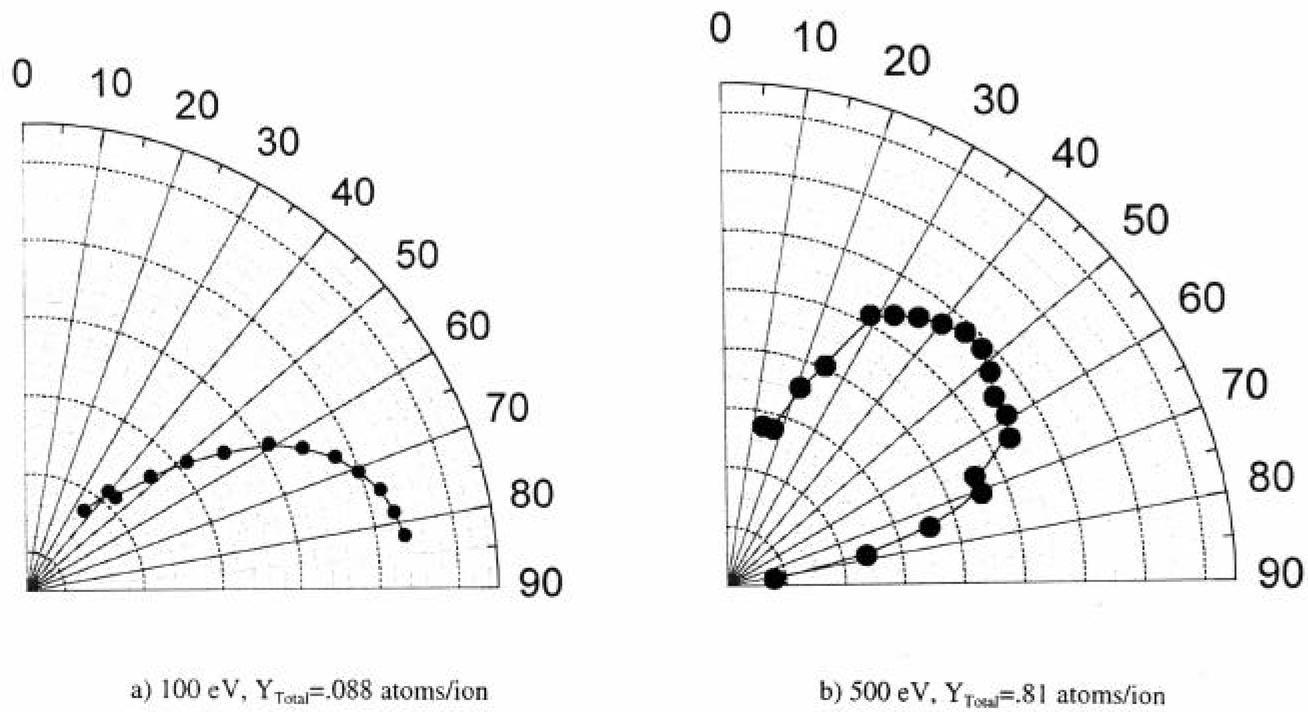

Fig. 4. Polar plot of differential sputtering yields of xenon-tantalum. (Arbitrary scale)

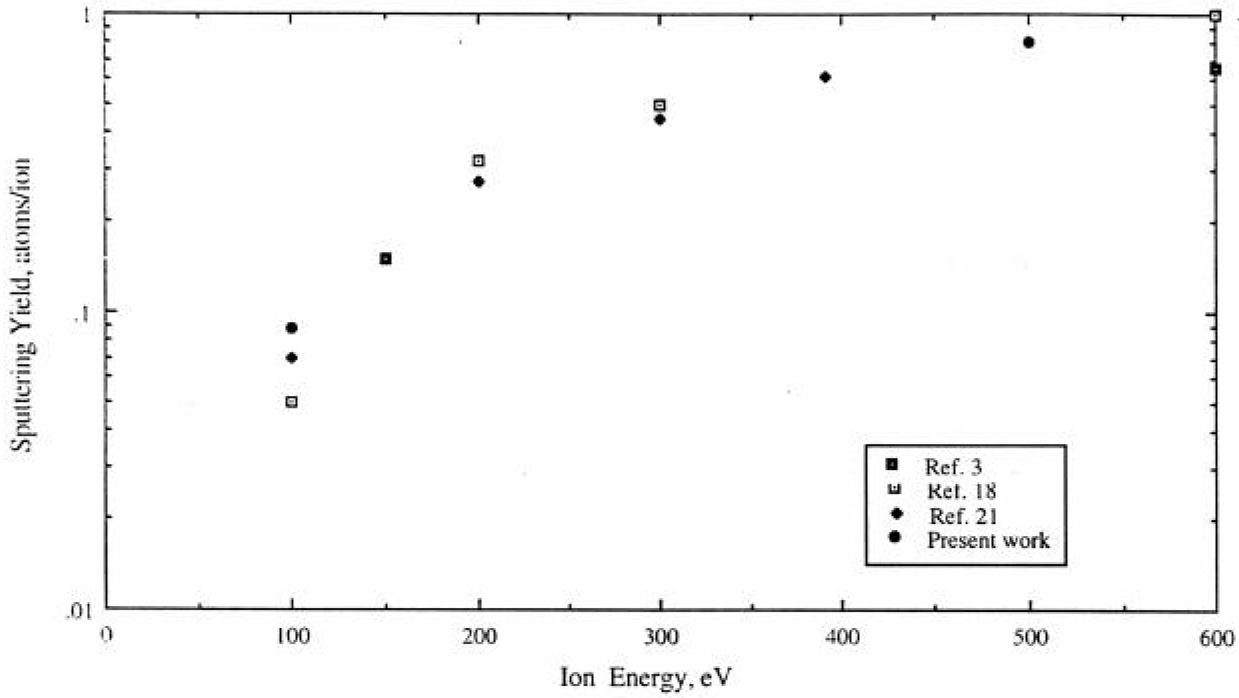

Figure 5. Measured sputtering yield of xenon-tantalum compared to literature data.