Development of Real-time Erosion Monitoring System for Hall Thrusters by Cavity Ring-Down Spectroscopy

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Sputter monitoring system using continuous-wave cavity ring-down spectroscopy (cw-CRDS) was built for both lifetime assessment and contamination effects in Hall thrusters. We have performed measurements of sputtered manganese atoms from acceleration channel wall (stainless steel 316) in an anode layer type Hall thruster. The measurement strategy is based upon detection of manganese atoms via an absorption line from ground state at a wavelength of 403.076 nm. The path-integrated number density is $1.4 \pm 0.3 \times 10^{13} \text{ m}^{-2}$ at a discharge voltage of 200 V and an argon mass flow rate of 70 sccm. The number density is proportional to the discharge voltage, as expected. The number density and mass-loss have a relatively linear dependence. These results show the validity of the erosion sensor for Hall thruster lifetime estimation.

Key Words: Hall Thruster, Lifetime, Cavity Ring-Down Spectroscopy, Erosion

Nomenclature

A_{ki}	:Einstein A coefficient, 1/s
Abs	:Absorbance
c	:Speed of light, $2.998 \times 10^8 \text{ m/s}$
E_b	:Binding energy, J
E_i	:Energy of state i , J
E_k	:Energy of state k , J
g_i	:Degeneracy of state i
g_k	:Degeneracy of state k
$k(\nu)$	:Absorption coefficient, m^{-1}
l	:Length of the ring-down cavity, m
N_i	:Lower state concentration, m^{-3}
R	:Mirror reflectivity
$S(t, \nu)$	:Ring-down signal
x	:Position along the optical axis
ν	:Laser frequency, Hz
τ	:Ring-down time, s
τ_0	:Empty cavity ring-down time, s

1. Introduction

Hall thrusters¹⁻³⁾ offer an attractive combination of high thrust efficiency (exceeding 50%) and specific impulse ($\sim 1500\text{-}3000 \text{ sec}$). In comparison to chemical rockets, the high specific impulse is attractive for large ΔV missions such as satellite positioning and station-keeping, and space exploration. Hall thrusters also have a higher thrust density than ion thrusters due to the existence of electrons in the ion acceleration zone. In addition, the lack of grids is attractive owing to the potential for reduced failures. Since the 1970s over 200 Hall thrusters have been operated in space. A key requirement for the practical use of Hall thrusters is the ability

to operate for long durations, for example a Hall thruster used for north-south station keeping (NSSK) of a commercial spacecraft will have to operate for over 5,000 hours over the course of its mission^{4,5)}. The primary life-limiter for Hall thrusters is acceleration channel wall erosion^{6,7)}. A thruster is generally considered to have reached end of life when the channel is fully eroded and the underlying magnetic yoke becomes exposed. The physical mechanism causing the erosion is sputtering of the channel material due to bombardment by energetic particles, primarily propellant ions having undergone radial acceleration. In addition to causing channel erosion and associated lifetime concerns, sputtered particles can redeposit on spacecraft components such as solar-arrays, thereby degrading their performance and potentially compromising spacecraft operation.

There have been many studies on the lifetime of Hall thrusters, including endurance tests^{4,5)}, numerical modeling^{8,9)} and direct measurement of erosion materials. These studies show that the erosion depends on operating condition, magnetic field configuration, wall material, anode configuration, and channel geometry. Understanding this dependence is essential for the practical application of Hall thrusters. It is not, however, practicable to validate the lifetime at each condition by means of typical wear tests because of the huge costs in time and money: several hundred thousand to millions of dollars and tie up valuable vacuum facilities and engineers for several months. What is needed, therefore, is a method of measuring thruster erosion rates non-intrusively in real- or near-real-time. The erosion rate can be measured by probing the eroded wall material in the plume. Such measurements would allow simultaneous evaluation of the impact of Hall thruster design changes on performance and lifetime.

The ideal diagnostic for *in situ* thruster studies should have high sensitivity to measure low erosion rates, the possibility

of integration to a thruster test-facility, and fast time-response to explore a range of operating conditions. Techniques such as weight loss¹⁰, collector plate¹¹, quartz crystal microbalance^{12,13}, radioactive tracers¹⁴, mass spectrometry¹⁵, and Rutherford backscattering¹⁶ each have certain advantages and can be appropriate for material sputter characterization studies but none readily meets all of the above criteria. The need for a sensitive nonintrusive measurement suggests the use of optical techniques. Optical emission spectroscopy (OES)^{17,18}, laser induced fluorescence (LIF)¹⁹ and multi-photon ionization coupled to a time of flight mass spectrometer^{20,21} have been used for species-specific sputtering measurements. The use of LIF has been particularly extensive and has proven to be very effective for velocity measurement though challenging for quantitative number density. OES is attractive owing to its experimental simplicity but the analysis can be challenging since collisional-radiative modeling (or similar) is required to extract number densities. Owing to these limitations, Laser Absorption Spectroscopy (LAS) has been proposed for erosion rate measurement⁹. LAS is a non-intrusive optical method with the potential advantage of providing directly quantitative number density measurements (meaning it does not require external calibration). Furthermore, LAS is amenable to *in situ* studies which can be conducted in near real-time. Our previous research showed the possibility of nonintrusive near real-time erosion measurement by LAS in an anode layer type Hall thruster⁹; however, the approach didn't yield sufficient sensitivity for number density measurements at needed conditions. The approach presented here builds upon our previous development of cavity ring-down spectroscopy (CRDS)²²⁻²⁴ for sputtering measurements. CRDS is a path-enhanced laser absorption method that provides the ultra-high sensitivity required to measure low erosion rates. Our current focus is to develop a CRDS lifetime sensor for Hall thruster erosion studies.

Past work at Colorado State University (CSU) has shown the use of pulsed-CRDS/continuous wave-CRDS to quantitatively measure sputter products²⁵⁻²⁹. We view that CRDS can function both as a method for sputter yield measurement and material characterization, to generate inputs for erosion and lifetime modeling; and can also provide an *in situ* diagnostic suitable to study thruster erosion and lifetime and aid in thruster design. Development of an *in situ* sputter sensor is underway in a collaborative effort between researchers at CSU, University of Michigan (UM), and Kyushu University (KU).

2. Detection of Sputtered Acceleration Channel Wall by Cavity Ring-Down Spectroscopy (CRDS)

2.1. Cavity ring-down spectroscopy

CRDS is a path-enhanced laser absorption method that provides the ultra-high sensitivity (down to sub-ppm levels per pass)^{22,23}. The technique is used extensively for trace-species measurement in flames, plasmas, and the atmosphere and we have developed its use for the study of sputtered particles in electric propulsion applications. The technique is directly quantifiable and can measure the ground

states. Measuring ground states can be advantageous since these levels typically contain a large fraction of the overall species population and their population fractions are less affected by collisional and radiative rates.

As shown in Fig. 1, the basic idea is to introduce an absorbing species (i.e. the sputtered atoms) into a high finesse optical cavity formed from high-reflectivity (HR) mirrors. The probe laser beam is coupled into the optical cavity where it “bounces” many times back-and-forth between the mirrors. Owing to the high reflectivity, the light within the cavity makes many passes within the cavity (e.g. $\sim 10^4$ passes for $R \sim 0.9999$), and the effective path length and thus sensitivity is greatly increased. A detector placed behind the cavity measures the temporal decay of optical intensity within the cavity. The difference in the temporal decay rate with and without the absorber (or with the laser tuned on/off the resonance) yields the sample concentration. The technique affords high sensitivity owing to a combination of long effective path length and insensitivity to laser energy fluctuations (since a rate is measured). Under appropriate conditions, the ring-down signal $S(t, \nu)$ decays single exponentially versus time as,

$$S(t, \nu) = S_0 \exp\left(-\frac{t}{\tau(\nu)}\right) \quad (1)$$

$$\frac{1}{\tau(\nu)} = \frac{l}{c} \left[\int k(x, \nu) dx + (1 - R) \right]$$

If the absorber is uniformly present over a column length l_{abs} , then $\int k(x, \nu) dx$ can be replaced with the product $k(\nu)l_{abs}$. In practice, the measured ring-down signal is fitted with an exponential, and the ring-down time τ is extracted. Combining τ with the “empty cavity ring-down time”, τ_0 (which in practice is measured by detuning the laser) allows determination of the sample absorbance, $Abs(\nu)$, and absorption coefficient:

$$Abs(\nu) = \int k(x, \nu) dx = \frac{l}{c} \left[\frac{1}{\tau} - \frac{1}{\tau_0} \right] \quad (2)$$

A commonly used approach is to scan the laser frequency across the absorption line and to measure the wavelength- (or frequency-) integrated spectrum (i.e. the line area). Assuming the spectroscopic line parameters are known, the measured area $\int Abs(\nu) d\nu$ of a transition from lower state i to upper state k can be readily converted to the path-integrated concentration of the lower state $\int N_i dx$ as:

$$\int N_i dx = \frac{\nu_{ki}^2}{c^2} 8\pi \frac{g_i}{g_k} \frac{1}{A_{ki}} \left(\int Abs(\nu) d\nu \right) \quad (3)$$

Fig. 1. The basic idea of CRDS.

Table 1. Transition data for manganese (from NIST database).

λ , nm (Air)	403.076
E_i , eV	0
E_k , eV	3.075
A_{ki} , s ⁻¹	1.7×10^7
g_i	6
g_k	8

For cases where the spatial distribution of particles is non-uniform, actual concentration profiles can be determined from the path-integrated concentration in several ways. For rough approximation one can assume a uniform concentration profile over a known column length, l_{abs} . Alternatively, Abel inversion or other inversion approaches based on inversion and modeled spatial profiles can be used³⁰⁾. CRDS can also be used to extract velocity information from the measured spectral lineshapes²⁸⁾.

2.2 CRDS detection of sputtered acceleration channel

The strategy for the erosion sensor of anode layer type Hall thruster is to detect manganese number density by cw-CRDS. In anode layer type Hall thrusters, conductive material, such as pyrolytic graphite or stainless steel and among other materials, is generally used for the acceleration channels. The acceleration channel in this study was made of stainless steel 316, and it contains about 1% manganese. So the erosion rate of the acceleration wall can be estimated by probing sputtered manganese atoms.

The target line is an absorption line from ground state to upper state ($3d^5 4s^2 \rightarrow 3d^5(^6S)4s4p(^3P^o)$) at 403.076 nm is selected based on their optical accessibility and high absorption strength. The transition data for this measurement are shown in Table 1, as quoted from the NIST database³¹⁾.

3. Experimental Setup

3.1. Experimental setup

Figure 2 shows a diagram of the experimental setup emphasizing the CRDS aspects. We use a tunable diode laser with external cavity (ECDL) to measure the transition line of manganese at 403.076 nm (Air). The mode-hop free tuning range of the laser is about 40 GHz and the laser linewidth is less than 5 MHz. The diode laser is set for a 25 GHz mode-hop-free frequency scan every 0.5 seconds (up- and down- scan in 1 s). The erosion rates could be found every 0.5 seconds. Inside the ECDL, an optical isolator is used to prevent back reflections into the diode laser cavity. The laser is coupled to a polarization maintaining (PM) single mode FC/APC fiber, which goes through the feedthrough into the vacuum chamber. An aspheric lens is used at the fiber exit to collimate the beam and to match the beam to TEM₀₀ mode of the cavity. An acousto-optic modulator (AOM) with a threshold detection circuit is used to extinguish the incoming laser beam. The total response time of the threshold circuit and AOM firing is less than 400 ns. Ring-down signals are measured with a 20 MHz 12-bit analog-to-digital acquisition board connected to a personal computer and a custom Labview© program is used for

Fig. 2. Schematic diagram of Mn monitoring system.

Fig. 3. Picture of optical cavity hardware on a rail-system Manganese Rail system. (a) without thruster, (b) with thruster.

exponential fitting with the nonlinear Levenberg–Marquardt method. A solid etalon (free spectral range=2.26 GHz) is used as a frequency reference.

The optical cavity length is 0.70 m and is formed by a pair of high reflectivity (HR) mirrors (Los Gatos Research, R>99.995%), each 25.4 mm in diameter with radius-of-curvature of 1 m. We typically operate with empty-cavity ring-down times of $\sim 20 \mu s$, corresponding to R $\sim 99.986\%$ (close to manufacturer's specifications). The optical cavity hardware is on a rail-system inside of the chamber, as shown in Fig.3. The rail system is mechanically and thermally isolated from the main chamber body by using polyurethane bumpers. The optical axis is 3 cm downstream of the thruster and it goes through the axis of the thruster. A series of irises held within a re-entrant tube are positioned in front of each cavity mirror to prevent deposition of sputtered particles and excess exposure to ultraviolet light, both of which can degrade mirror reflectivity. Light exiting the cavity is relayed via a multi-mode (MM) optical fiber to a PMT outside the vacuum chamber. A dielectric interference filter (40 nm band-pass) and an iris are used to suppress background light and emission from the plasma.

3.2. Anode layer type hall thruster

Figure 4 shows a cross-section of the 1 kW class anode layer type Hall thruster used in the current experiments. The inner and outer diameters of the acceleration channel are 48 mm and 72 mm respectively. An inner solenoid coil and four outer solenoid coils create a predominantly radial magnetic field in the acceleration channel, as shown in Fig. 5. The magnetic flux density is varied by changing the coil

current. The magnetic field distribution along the channel median is shown in Fig. 5(a) and the calculated magnetic field lines is shown in Fig. 5(b) (each coil current is 1 A, calculated using Magnum2.5, Field Precision LLC.). The origin of Fig.5 is the exit of the acceleration channel, and the radial magnetic flux density has peak at $z = -1$ mm. Magnetic flux density is higher on the inner wall and decreases with radius, since the magnetic flux between the poles is conserved. In these experiments, the acceleration channel is made from stainless steel (SUS316). The SUS 316 contains about 1%

Fig. 4. Cross section of the Anode layer type Hall thruster developed at Kyushu University.

Fig. 5. Magnetic field configuration of the Hall thruster developed at Kyushu University. (a) Radial magnetic flux density profile (outer coil current = 1 A, inner coil current = 1 A, $r = 30$ mm) (b) Calculated magnetic field lines (Calculated using Magnum2.5, Field Precision LLC.)

manganese (0.81% from manufacturer's datasheet) and, as discussed below, the CRDS measurements are based on detection of the manganese sputtered from the channel wall. The separation between the acceleration channel wall and the anode is 1 mm. The thruster has a hollow annular anode, which consists of two cylindrical rings, with a propellant gas fed through them. The width of the hollow anode is 8 mm, and the gap between the tip of the anode and the exit of the acceleration channel is fixed at 3 mm. 99.999% High-purity argon gas was used as the propellant with thermal mass flow controllers (Brooks 5850E).

Tests are conducted in a vacuum chamber of 1.5 m diameter by 4.6 m length. A hollow cathode is used as the electron source. The pumping system includes a dry mechanical pump (Edwards GV250), assisted by a mechanical booster pump (Edwards EH-1200) and two diffusion pumps (Varian HS-20). The chamber baseline pressure is below 7×10^{-4} Pa. Any contribution of sputtered manganese from the chamber wall is negligible owing to the chamber wall material (soft iron) and position of the Hall thruster.

4. Results and Discussions

Concentration measurements are determined from the area of absorption spectra, as shown in Fig. 6. To construct the spectrum, we use a binning approach, dividing the frequency axis into a series of bins, each with width 1 GHz, and signals falling within the bin are averaged. The path-integrated manganese number density is estimated using equation (3). The laser tuning range is insufficient to scan over the full line width so we find the line area by numerically integrating half of the lineshape (the low-frequency side of the peak) and doubling. In future work other scanning and fitting methods could be used. For the condition that discharge voltage = 200 V and argon anode mass flow rate = 70 sccm, the path-integrated Mn concentration is $1.4 \pm 0.3 \times 10^{13} \text{ m}^{-2}$ (where the uncertainty is partly due to the area fitting but dominated by the 18% uncertainty in A_{ki}). In principle the measured concentration corresponds to the directly measured ground state, but because there are no low-lying levels the ground state and overall Mn populations are equivalent (to within our uncertainty). More precisely, a Boltzmann analysis for a characteristic temperature of 1500 K shows that the ground state comprises >99% of the overall population. It is interesting to note that owing to lack of equilibrium in the sputtering process (and lack of collisions after ejection) there is little reason to assume Boltzmann distributions for the sputtered particles; nonetheless, past research has generally shown distributions similar to Boltzmann with "temperatures" generally in the range ~500-1500 K. (In some cases elevated "anomalous" populations of sputtered particles in higher lying energy levels have been observed, but the agreement between our CRDS and mass-loss makes it unlikely that such effects are significant in these experiments.) One should also consider the possibility that sputtered ground state atoms are excited to a higher level, or ionized, prior to reaching the measurement location, but simple calculations show the loss

Fig. 6. Absorption profile of target spectrum at discharge voltage of 200 V and argon anode mass flow rate of 70 sccm.

Fig. 7. The sputtered manganese number density measured through the thruster plume vs. mass-loss of one-hour duration for three different discharge voltages.

of ground state atoms owing to these effects to change the signal by <10% at our conditions.

We have performed an initial study of dependence of sputter erosion on discharge voltage (150 V, 200 V, 250 V). Figure 7 shows the sputtered manganese number density measured through the thruster plume vs. mass-loss of one-hour duration for three different discharge voltages. The path-integrated number densities are determined from the CRDS as described above. For these conditions, the sputtered particle number density increases roughly linearly (or slightly more strongly) with discharge voltage. This is reasonable since a sputtering yield increases with the argon ion energy colliding with wall, and argon ion energy increases with the discharge voltage. The mass-loss values are found by measuring the mass change of the stainless steel channel at the corresponding condition (with uncertainty of 5% due to scale resolution and small changes in thruster operation conditions). The trend of mass-loss versus discharge voltage is in broad agreement with that for the CRDS results.

The manganese number density deduced by CRDS is proportional to the direct mass-loss measurements, thereby providing rough validation of the CRDS results. This is reasonable since if we assume a Thomson distribution³²⁾ for particle velocity (energy) using the binding energy of Mn ($E_b = 2.92$ eV) and $n=1.54$ as the exponent on the velocity distribution:

$$f(V) \propto \frac{V^3}{(V^2 + V_b^2)^{n+1}} ; V_b = \sqrt{\frac{2E_b}{M}}. \quad (4)$$

The sputtered atom velocity distribution is constant even if the energy of the ions colliding with the wall is changed. That is, the number densities of sputtered atoms would be proportional to the mass-loss of the acceleration channel for rough estimation (of course, we should consider the effect of the difference of the ionization region with changing the operational parameter, and other factors). We have also used a finite element model to determine the flux of sputtered particles, and associated mass change, from the CRDS measurements, and find the results of this analysis to be in good agreement with the mass loss measurements³³⁾.

5. Summary

The cw-CRDS real-time sputter monitoring system reported here is, to the best of our knowledge, the first such demonstration. The demonstrated cw-CRDS sensor used a diode laser at 403 nm to probe manganese atoms sputtered from the stainless steel acceleration channel of a 1 kW class anode layer Hall thruster. The optical cavity was fiber coupled in and out of the vacuum chamber. The flexibility of such an approach is amenable to implementation in different vacuum chamber facilities. We have compared the number density estimated from the cw-CRDS technique and the mass-loss of one-hour duration for three different discharge voltages. The relation between the number density and mass-loss shows a relatively linear dependence as would be expected based on a simple analysis, thereby providing initial validation of the sensor. Furthermore, the high time response and /in situ/ nature of the CRDS sensor can be of great utility in understanding erosion rate trends, i.e. monitoring how the erosion signal varies with changes in thruster operating conditions.

The aforementioned results showed that cw-CRDS based sensors should allow (near) real time measurements of sputter erosion in Hall thrusters, thereby providing a new and powerful tool for sputter erosion and lifetime studies. Indeed, we are currently developing a similar erosion sensor for magnetic layer type Hall thrusters. This sensor employs cw-CRDS with a frequency-quadrupled diode laser to detect sputtered boron from the boron nitride insulator channel. Initial tests show a minimum detectable absorbance of 20 ppm for detection times of ~1 minute which should be very adequate for many thruster conditions³⁴⁾.

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