Hall Thruster Erosion Measurement

by Time-Resolved Cavity-Ring Down Spectroscopy

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The life limiter of Hall thruster is ion bombardment on the acceleration channel. To estimate the lifetime of the thruster, sputtered atoms should be measured. However, the conventional method, the endurance long term test requires a huge amount of time and money. Therefore, erosion sensor using cavity ring-down spectroscopy has been developed. In this study, we measured the sputtered aluminum atoms oscillating with the discharge current oscillation by our time-resolved CRDS system.

Nomenclature

A_{ki}	=	Einstein A coefficient
c	=	light speed
g_i	=	lower level degeneracies
g_k	=	upper level degeneracies
k	=	absorption coefficient
L	=	cavity length
R	=	mirror reflection
S	=	ring-down signal
t	=	time
x	=	laser direction
ν	=	laser frequency
ν_{ki}	=	transition frequency
τ	=	ring-down time
τ_0	=	ring-down time under vacuum
ABS	=	absorbance
ABS_{min}	=	minimum detection

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I.Introduction

In past a few decades, Electric propulsion achieved more than 5,000 hours lifetime and succeeded in various space missions[1-2]. According to these successes, Electric propulsion has caused widespread concern as a thruster in a lot of missions. As a result, thruster of longer lifetime was required. To extend the lifetime, it is necessary to optimize thruster's shape and magnetic field configuration

Lifetime limiter of the Hall thruster is wear of thruster's wall due to sputter erosion[3]. Lifetime of the thruster can be evaluated from the erosion rate of the thruster. However, the conventional measuring method, durability test spends tremendous cost both in the manpower and the time[4]. Moreover, measuring parameters such as anode shapes and magnetic field configurations are enormous and the erosion is infinitesimal, so that fast time response and high sensitive sputter erosion measurement system is required. Considering these requests, sputter measurement system using cavity ring-down spectroscopy (CRDS) for electric propulsion has been developed at Colorado State University[5-6].

CRDS is a path-enhanced laser absorption method[7-10]. It has two high reflective mirrors consisting optical cavity and laser passes into the cavity. When the sputter particles are inside the cavity, the particles eat the laser and attenuation time of the transmitted light shorten. From the time difference, the particle density can be obtained in situ under non-intrusive, ultra-high sensitive and directly quantifiable measurement. This system enables sensitivity of measurement to be improved more than 10,000 times as large as the laser absorption spectroscopy due to extension of the optical path. In addition, it only needs to measure attenuation of transmitted light. Thus, it is not necessary to measure incident light and penetrating light.

In previous research using the CRDS system, we observed plasma fluctuation which degraded the minimum detection limit[11]. Hence, we developed the time-resolved CRDS system, which can measure fluctuated erosion rate synchronizing with the thruster's fluctuation by using 200 W Hall thruster which was developed at Kyushu University.

II.Experimental

A. CRDS system

Figure 1 shows an outline figure of CRDS system. An excitation light was emitted from external cavity diode laser (ECDL) and the wavelength was swept from 394.509 to 394.512 nm to measure the transition line of. aluminum at 394.512 nm[12]. The mode-hop-free scanning range was approximately 20 GHz and laser linewidth was less than 10 MHz.

The modulated laser was separated into several passes by beam splitters for probe and wavelength reference. The probe light was chopped by the trigger when the ring-down signal was larger than threshold. The, the light was modulated to the first-order diffracted light using an acousto-optic modulator (AOM). A neutral density (ND) filter was used to prevent the absorption saturation. The laser path was 12 mm downstream from Hall thruster exit. An optical cavity was composed of high-reflection mirror (R>99.95%) and cavity length was 0.55 m. A photomultiplier tube (PMT) detected the transmitted signals and they were recoded. The reference light was used to determine the relative frequency to the absorption frequency of aluminum by optogalvanic spectroscopy. The light was chopped by optical chopper and passed through the HCL. The aluminum spectrum has several peaks because of hyperfine structure so that the optogalvanic signals were fitted based on the sum of three Gaussian functions[13-14].

In this study, Volterra system was sued to control the discharge current oscillation and it was synchronized with the time-resolved CRDS measurement. The Volterra Engine is a one of power processing unit to control the discharge current oscillation.[15-16] Then, the time of the obtained ring-down signal was aligned to the normalized time in the oscillation. Thus, the ionization instability in the Hall thruster could be controlled and the discharge current oscillation could be locked at the applied frequency. The time resolution was set to 10 μs, i.e., one fifth of the oscillation cycle. The wavelength resolution was set to 1 GHz.

The normalized time was defined as

$$\text{Normalized time} = \frac{t}{T} \tag{1}$$

where t is the time difference from the maximum peak to the peak of the ring-down signal and T is the cycle of the discharge curren.

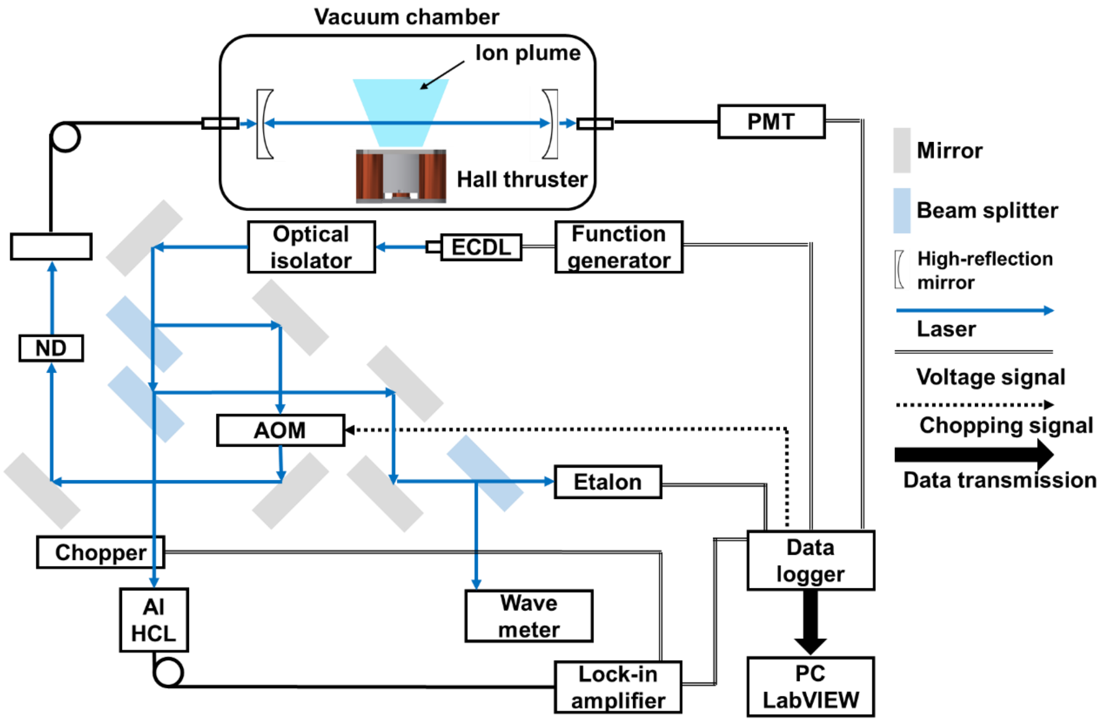

Figure 1. Schematic diagram of the developed CRDS system.

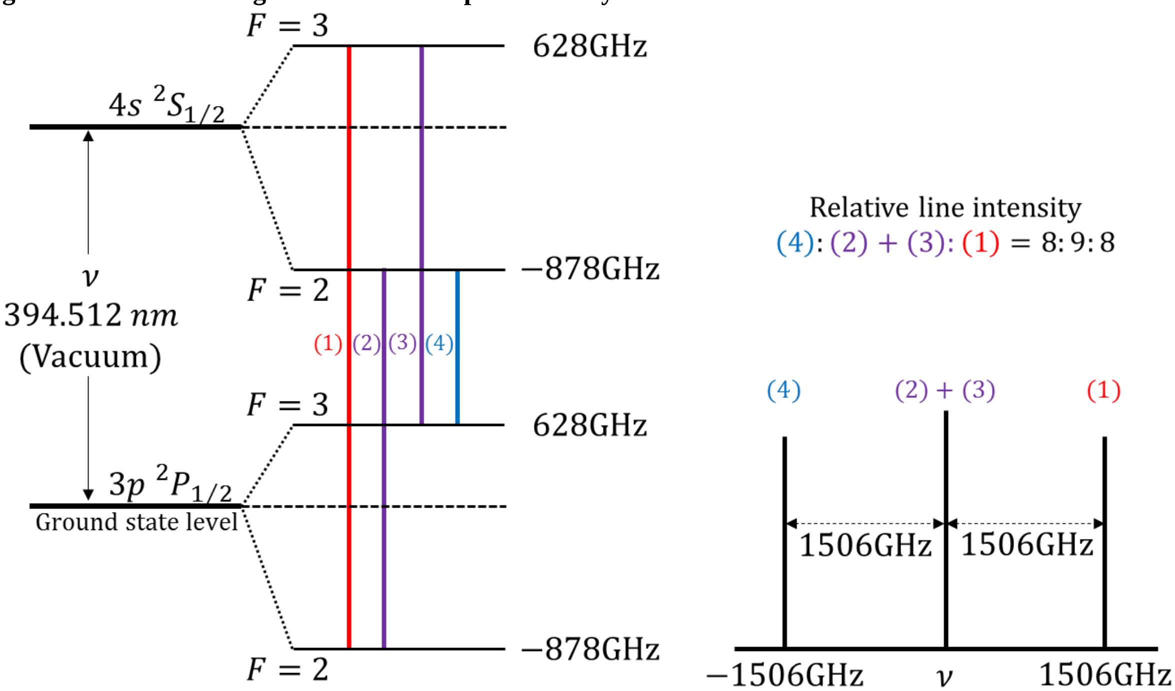

Figure 2. Hyperfine structure of aluminum.

B. Hall thruster

In this study, a 200 W magnetic-layer-type Hall thruster, which was developed at Kyushu University was used.

a hollow cathode (Veeco, HC252) was used as the electron source and the reutilizer. The inner and outer diameters of the Hall thruster were 34 and 59 mm, respectively. The anode was set 25 mm upper from the thruster exit. For the insulation, a composite sintered ceramic based on AlN and BN was used for the wall material. The thruster had 4 solenoid coils at each corner and a solenoidal coil at the center of the thruster. The magnetic flux density and configuration could be changed by controlling the ratio of the inner coil current to the outer coil current.

The propellant xenon gas was controlled by a mass flow controller. During the Hall thruster operation, the anode mass flow rate was 0.68 mg/s and the cathode mass flow rate was 0.27 mg/s. In addition, argon gas was blown on the high-reflection mirror at the mass flow rate of 0.15 mg/s to keep the ring-down time to restrain contamination of the mirror by sputtered particles from the wall and vacuum chamber.

C. Vacuum facility

The experiment was carried out in a cylindrical vacuum chamber whose size was 1.2 m in length and 1.0 m in diameter. The wall inside the chamber consisted of aluminum-free SUS304 stainless steel so that the vacuum facility did not affect the CRDS measurement of aluminum. This facility was equipped with a rotary pump, two turbomolecular pumps, and a cryogenic pump. The ultimate pressure was less than 2.8×10^{-4} Pa and an operating pressure was 3.0×10^{-2} Pa.

III.Results and discussion

A. Absorbance

Figure 3 shows the time-averaged spectrum obtained by the ring-down time. In the calculation process of the ring-down time, the ring-down signals were fitted by using the signals in the first 5 μs to enhance the time resolution. The peak was observed at around 0 to 2 GHz, that is, the sputtered aluminum atoms were measured.

Figure 4 shows a histogram of the absorbance of the bin from 0 to 1 GHz. As seen in Fig. 3, the uncertainty was around 35 ppm, however, the histogram was conformed to Gaussian distribution. The uncertainty can be evaluated by the standard error. In this case, the uncertainty was evaluated as 6.36 ppm.

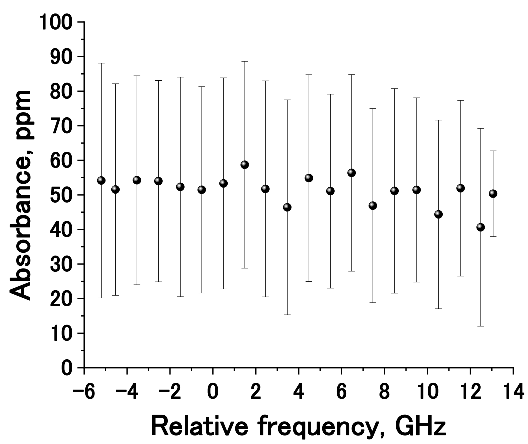

Figure 3. Time-averaged spectrum.

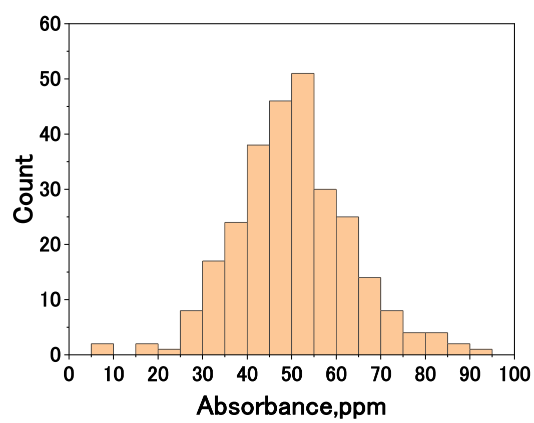

Figure 4. Histogram of the absorbance of the bin from 0 to 1 GHz..

B. Time-resolved CRDS

Figure 5 shows the time-resolved CRDS absorbance. When the normalized time was 0.0 to 0.2 and the relative frequency was 0 to 2 GHz, the absorbance was large, and when the normalized time was 0.5 to 0.7 the absorbance was small. It was observed that the absorbance was fluctuated by the discharge current oscillation.

Figures 6, 7,8,9, and 10 present histograms of the time-resolved absorbance in the 0 to 1 GHz bin for normalized times of 0.0–0.2, 0.2-0.4, 0.4-0.6, 0.6-0.8 and 0.8–1.0, respectively. The central axes of histogram were shifted. This would be because the number of sputtered atoms varied over time. This time, we used time-resolved CRDS to suppress the dispersion of histogram, however, in this case, the standard divisions were not improved and the distribution were also not conformed to Gaussian distribution. Therefore, the uncertainty was not improved by time-resolved CRDS in this case.

Figure 9 shows the absorbance spectrum for a normalized time of 0.4–0.6. To obtain the linear density, the spectrum was fitted using six Gaussian functions considering the three isotope shifts. The amount of aluminum was estimated for each normalized time. The fitting error was approximately 19%. Then, the linear density was calculated as

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

where g_i is the lower-level degeneracy, g_k is the upper-level degeneracy, ν_{ki}^2 is the transition frequency, c is the speed of light, and A_{ki} is the Einstein A coefficient.

Figure 10 shows the time variation of the linear density of titanium atoms with the discharge current and the discharge voltage. The linear density oscillated from $7.9\times10^{12}/\mathrm{m}^2$ to $9.1\times10^{12}/\mathrm{m}^2$ with the discharge current and appeared to lag slightly behind the discharge current.

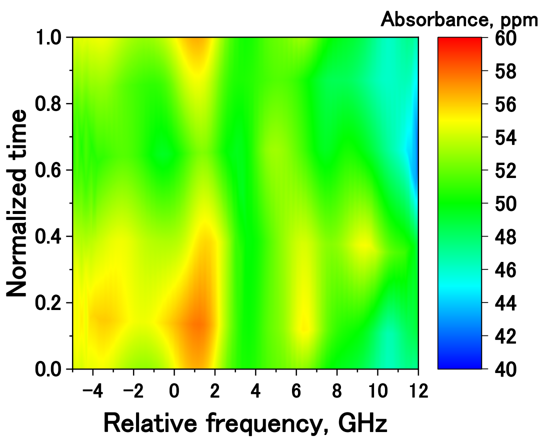

Figure 5. Time-resolved CRDS absorbance.

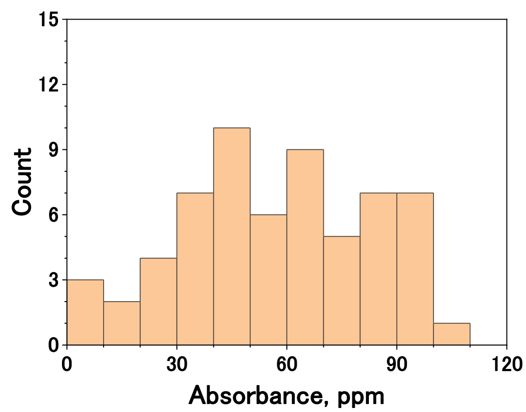

Figure 6. Histogram of the time-resolved absorbance in the 0 to 1 GHz bin for a normalized time of 0.0–0.2.

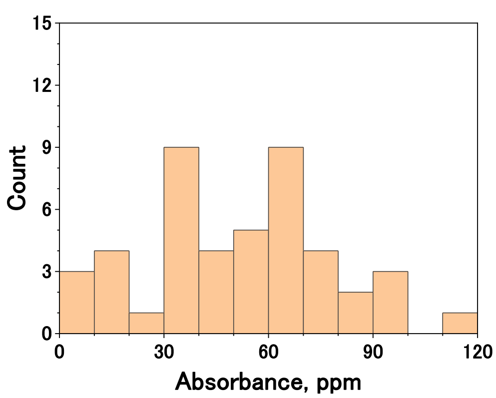

Figure 7. Histogram of the time-resolved absorbance in the 0 to 1 GHz bin for a normalized time of 0.2–0.4.

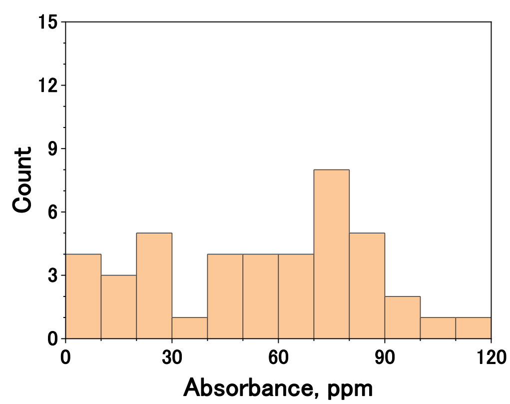

Figure 8. Histogram of the time-resolved absorbance in the 0 to 1 GHz bin for a normalized time of 0.4–0.6.

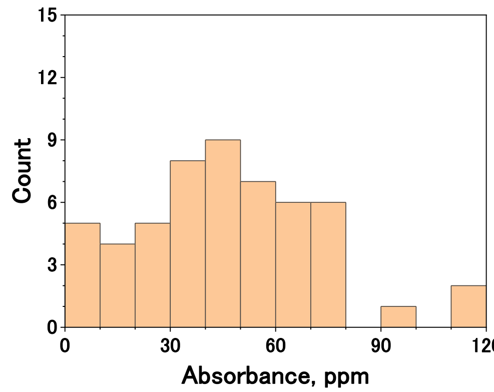

Figure 9. Histogram of the time-resolved absorbance in the 0 to 1 GHz bin for a normalized time of 0.6–0.8.

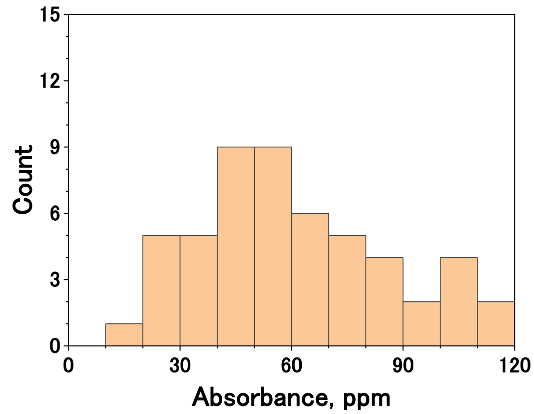

Figure 10. Histogram of the time-resolved absorbance in the 0 to 1 GHz bin for a normalized time of 0.8–1.0.

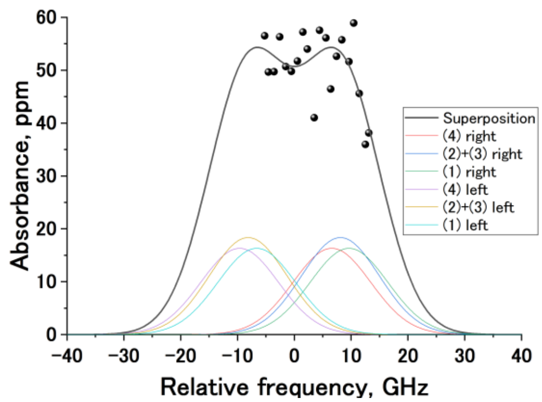

Figure 11. Absorbance spectrum for a normalized time of 0.4–0.6

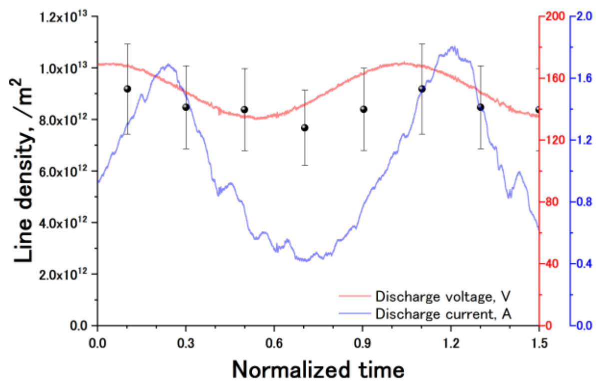

Figure 12. Time variation of the linear density of titanium atoms.

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