Development of Lifetime Evaluation Method Using Multilayer Coating Chip

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(Received August 18th, 2009)

In order to improve Hall thruster's lifetime performance, A new lifetime evaluation method, lifetime estimation using multilayered coated chips was developed for channel wall erosion rate distribution measurement. This method uses small chips coated with alternate channel wall material and marker. By detecting the marker emission as a signal of erosion progress, this method enables direct and rapid erosion rate distribution measurements. In this study, the capability of this new method for erosion rate distribution measurement was tested and validated. Multilayer coated chips of two kinds using different marker metals were embedded into the acceleration channel wall. The channel-wall erosion rate distribution was then measured. The measured erosion rates were, respectively, 0.90 nm/s and 0.75 nm/s at 2 mm and 4 mm upstream from the channel exit.

Key Words: Hall Thruster, Lifetime Evaluation, Multilayer Coating, Sputtering

Nomenclature

S	: sputter yield against Xe^+
N	: Xe^+ beam flux, $\text{mol}/(\text{m}^2\cdot\text{s})$
M	: atomic weight, kg/mol
ρ	: density, kg/m^3
v	: erosion rate, m/s

Subscripts

i	: ion
t	: target

1. Introduction

A Hall thruster is a promising electric propulsion system because of its high specific impulse and thrust efficiency¹⁾. Like other electric propulsion systems, an important Hall thruster performance criterion is its lifetime because typical missions require continuous operation for up to 10,000 hr²⁾.

The Hall thruster lifetime is determined by erosion of the acceleration channel wall by ion sputtering. To improve the Hall thruster lifetime performance, development of lifetime estimation methods is necessary. Among the various proposed erosion rate measurement methods^{3), 4)}, lifetime estimation using multilayer coated chips is a useful one because of its short measurement time and capability of erosion-rate distribution measurement. In our previous study, we conducted erosion rate measurement at the channel exit⁵⁾. In this study, this new method was developed further for spatial distribution measurement.

The Hall thruster's channel-wall erosion rate depends strongly on the axial position⁶⁾. To evaluate the lifetime performance of a Hall thruster precisely, and to validate the results of numerical simulation, it is necessary to measure the

spatial distribution of the channel wall erosion rate. For this purpose, lifetime estimation using multilayer coated chips is useful because of its high spatial resolution. Therefore, the objective of this study is to conduct erosion rate distribution measurements using this new method.

Multilayer coated chips of two kinds with different marker metals were embedded into the Hall thruster channel wall. Then the emission signals of both marker metals were observed simultaneously. Results show that the erosion rate distribution was measured successfully.

2. Experiment

2.1. Principle of the measurement method

Figure 1 presents a schematic of the lifetime estimation method using multilayer coated chips. A multilayer coated chip is embedded into the Hall thruster channel-wall. The multilayer film on the chip comprises alternate thin metal layers and thick ceramic layers. The thin metal layers are used as markers to detect the erosion rate of ceramic layers, whereas the thick ceramic layers represent the ceramic channel wall. When the Hall thruster operates, ion sputtering erodes the embedded chip and the surrounding channel wall. The emission of marker metal sputtered out from the thin metal layers is observed using emission spectroscopy. The spectrometer will detect the eroded marker metal as emission peaks. The channel wall erosion rate is therefore calculable from the intervals of periodic peaks of emission signals.

Erosion rate measurements can be done much more quickly using this method, in less than half an hour. Furthermore, the emission intensity fluctuation has no influence on accuracy, which is an important advantage over other real time erosion rate measurement methods. Moreover, this method has high spatial resolution because of the small multilayer coated chips.

Fig. 1. Schematic of the lifetime estimation method using multilayer coated chips. The erosion rate is calculated from intervals of periodic emissions of metal layers.

2.2. Erosion rate distribution measurement

Figure 2 presents a diagram of the erosion rate distribution measurement. Multilayer coated chips containing different marker metals are embedded into the acceleration channel wall. When the Hall thruster operates and the chips and channel wall are eroded, each chip emits a distinct characteristic emission of its marker metal. Observing the emission history of all marker metals simultaneously enables real-time erosion rate distribution measurements. As the first step of measurements, chips of two kinds were used for this study.

Fig. 2. Schematic of erosion rate distribution measurement. Each marker measures the channel wall erosion rate at the point where it is embedded. Two chips of different materials were used for this study.

2.3. Multilayer coated chip

The marker metal material was chosen as follows.

The erosion rate of a target material against the ion beam can be shown as presented below.

$$v = N_i S \frac{M_t}{\rho_t} \quad (1)$$

All parameters on the right-hand side except N_i depend on the material of the target. We define κ_t as follows.

$$\kappa_t \equiv S \frac{M_t}{\rho_t} \quad (2)$$

Material with high values of S and κ_t is appropriate for use as a marker. High S means a high number density of marker material in the channel when the marker layer is eroded, which makes emission easier to detect. High κ_t denotes a high marker-layer erosion rate, which shortens the time needed to erode marker layers. It therefore enhances the accuracy of measurement as a result.

Table 1 shows sputter yields and κ_t against the Xe^+ beam of

several marker candidates. Taking the availability of the material into consideration, Cu and Ag were used as marker metals in this study. Although Cu is also used as an anode material of the Hall thruster, the erosion rate measurement will show no interference by the emission of Cu from anode because the absolute value of the emission peak intensity is not necessary in this method. Only detection of the emission peaks is necessary.

Figure 3 shows multilayer coated chips used for this study. The chip base material is SUS304. Their diameter is 1 mm. Three marker layers and two BN layers were coated alternately. The respective BN, Cu, and Ag layer thicknesses were 170 nm, 43 nm, and 17 nm. The Cu layer was coated much more thickly than the Ag layer because we placed priority on detecting the emission peaks of Cu. Chips were insulated from the thruster to avoid interfering with the Hall thruster operation.

The multilayer coated chips were manufactured using an ion beam sputtering coating device. The coating process was conducted at the Smart Processing Research Center, Osaka University. Table 2 shows the operation conditions of the coating device. To produce a coating layer precisely, the coating rate of each material was measured in advance. The results were 0.96 nm/min, 8.8 nm/min, and 43 nm/min, respectively, for BN, Ag, and Cu.

Table 1. Characteristics of marker candidates.

Material	Sputter yield				κ_t cc/mol
Ion energy, eV	100	200	300	600	200
Cu	0.26	0.79	1.29	2.44	5.64
Ag	0.40	1.05	1.80	4.20	10.8
Pt	0.19	0.72	1.25	2.23	6.55
Au	0.16	1.00	1.83	3.10	10.2
Al	0.06	0.24	0.45	1.02	2.40
Fe	0.06	0.29	0.54	1.2	2.06
Ti	-	0.13	0.24	0.5	1.38

Table 2. Operation conditions of coating device.

Parameter	Value
Working gas	Argon
Mass flow rate	0.20 mg/s
Acceleration voltage	1000 V
Deceleration voltage	-500 V
Ambient pressure	7.9×10^{-3} Pa

Fig. 3. Schematic of multilayer coated chip. Chips were insulated from the thruster to avoid affecting the thruster operation.

Table 3. Operation conditions of Hall thruster.

Parameter	Value
Propellant	Xenon
Mass flow rate	1.08 mg/s
Discharge voltage	150 V
Discharge current	2.0 A
Magnetic flux density	18 mT
Ambient pressure	2.5×10^{-2} Pa

Fig. 4. Cross section of the 500 W class UT Hall thruster.

2.4. Hall thruster

Figure 4 shows the 500 W class magnetic layer type Hall thruster developed at The University of Tokyo. The inner and outer diameters of the acceleration channel are, respectively, 22 mm and 30 mm. The channel length is 14-mm long and the wall material is boron nitride (BN). The operation conditions are presented in Table 3.

Multilayer coated chips were lined up in the axial direction. The Ag and Cu chips were set respectively 2 mm and 4 mm upstream of the thruster exit on the outer acceleration channel-wall. The presence of multilayer coated chips did not affect the Hall thruster operation. The operation parameters of the Hall thruster were identical, irrespective of whether the chips were embedded or not.

Fig. 5. Schematic of the measurement system. Collection optics were focused on the channel exit where the chips were lined up.

Table 4. Measurement setting of optical system.

Parameter	Value
Sampling rate	1 Hz
Exposure time	1 s
Wavelength range observed	310–350 nm
Wavelength resolution	0.04 nm

Fig. 6. Emission history of Ag I (328 nm) and Cu I (324.8 nm). The emission intensity is normalized for simplification. Three peaks for Ag and one peak for Cu were observed.

Fig. 7. Emission history of Cu I (324.8 nm). Two emission peaks of Cu were observed.

2.5. Optical system

Figure 5 shows the optical system. The collection optics was focused on the channel exit plane, where the chips were lined up. The emission history of Ag I (328 nm) and Cu I (324.8 nm) were measured simultaneously using the same spectrometer. Table 4 shows the spectrometer measurement setting. The dead time of the spectrometer was negligible.

3. Results and Discussion

Figure 6 shows the emission history of marker metals Ag (328 nm) and Cu (324.8 nm). Peaks of emission signal of both marker metals were observed. Three peaks of emission signals for Ag and one for Cu were detected.

The first peak and second peak of Ag are very close, which presumably results from the unstable ignition of the Hall thruster, which caused a very high erosion rate⁷⁾. The Hall thruster operation was stable after the second peak of Ag was observed. The interval of second and third emission peak of Ag was 190 s; the BN erosion rate calculated from the interval was 0.90 nm/s, which is a reasonable value compared with that of SPT-100⁶⁾.

The first peak of Cu is delayed because the chip was embedded too deeply into the channel wall. Because of the malfunction of the Hall thruster, the observation was stopped before the second and third peaks of Cu emission were to be observed. Second and third emission peaks would have been observed with longer operation.

The emission history of Cu was observed separately afterward under identical experimental conditions. The result is shown in Fig. 7. Two emission peaks of Cu atoms were observed. The second emission peak was dull. Therefore, the peak center was determined using Gauss fitting. The erosion rate calculated from the interval of two peaks was 0.75 nm/s. The third marker layer's emission peak could not be observed. Presumably, the third peak was too collapsed to be detectable.

The emission peaks of Ag and Cu were observed simultaneously; the erosion rates at two different places at the channel wall were measured. The calculated erosion rate was faster at the place nearer the channel exit. This tendency is reasonable compared with measurements conducted through a long time of operation⁶⁾.

4. Conclusion

This study confirmed that the multilayer coating method can provide an erosion rate distribution measurement.

Multilayer coated chips of two kinds using Cu and Ag as marker metals were embedded into a Hall thruster acceleration channel. The emission histories of both marker metals were observed simultaneously. The peak emission signals of the respective marker metals were observed. The erosion rates calculated from intervals of emission peaks were, respectively, 0.90 nm/s and 0.75 nm/s at 2 mm and 4 mm upstream from the channel exit. The measured erosion rate distribution was reasonable.

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