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Hall Thruster Channel Wall Erosion Rate Measurement Method Using Multilayer Coating Chip

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Lifetime problem is extremely important for a Hall thruster because most missions require more than 10,000 hr operation. Hall thruster's primary lifetime-limit is caused by channel wall erosion. Since conventional erosion measurement methods require long time operation, it is important to develop a fast erosion measurement method to investigate erosion problem and to reduce erosion rate. An erosion rate measurement method using multilayer coating chips is developed for this purpose. This method accelerates the channel wall reduction rate measurement by using small chips with alternate very thin coating layers. The objective of this study is to demonstrate the usefulness of this method. The relationship between magnetic flux density and channel wall erosion rate was examined, and the result was compared with that of conventional emission spectroscopy. In addition, axial distribution measurement of channel wall reduction rate was also conducted.

Nomenclature

S = sputter yield
N_i = ion beam flux
M_t = atomic weight of target material
ρ_τ = density of target material
κ_t = volumetric sputter yield
v = channel wall reduction rate
t = time
I = emission intensity of marker metal
T_{BN} = thickness of BN layers
T_M = thickness of marker metal layers

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I. Introduction

A Hall thruster is a promising electric propulsion system because of its high specific impulse and thrust efficiency.[1,2] Like other electric propulsion systems, an important Hall thruster performance criterion is its lifetime since most missions require continuous operation for more than 10,000 hr.[3]The Hall thruster lifetime is determined by erosion of the acceleration channel wall by ion sputtering. Accelerated Xe ions impinge the ceramic channel wall and knock out channel wall molecules. Therefore, development of channel wall erosion measurement methods is necessary to improve its lifetime performance. In addition, the Hall thruster's channel-wall erosion rate depends strongly on the axial position.[4] In order for accurate lifetime performance evaluation and for validation of numerical simulations, the development of methods which can measure the spacial distribution of channel wall erosion rates is requested.

Existing measurement method can be classified into two groups.[5,6] The first group is long time operation, which measures the channel wall reduction directly after hundreds to thousands of hours of thruster operation. This kind of methods can accurately measure the channel wall erosion rate with high spatial resolution. However, since enormous time is required, these methods cannot measure the time varying erosion rate, and is difficult to conduct. The second group is measurement using spectroscopy. Instead of direct erosion measurement, these methods observe the emission of eroded channel wall molecule in the acceleration channel, so that real-time erosion measurement is enabled. However, this group of methods can only measure the relative value of total erosion amount of the thrust, and can neither measure the absolute value of erosion, nor erosion rate at a specific point.

Channel wall erosion rate measurement method using multilayer coating chip (multilayer coating method) is a new erosion rate measurement method developed in our laboratory. This method combines advantages of both existing groups of methods, and has three major merits: short measurement time, direct erosion rate measurement, and fine spatial resolution. Despite using spectroscopy, this method can measure the absolute value of erosion, and capable of spacial distribution measurement. Therefore, this new method will be a powerful tool for repetitive erosion measurements under different conditions, and for validation of numerical erosion simulations.

The objective of this study is to demonstrate the usefulness of multilayer coating method. The erosion rate at the exit of acceleration channel wall of a Hall thruster was measured, and the relation of magnetic flux density and erosion rate was examined. In addition, spatial distribution measurement of channel wall reduction rate was also conducted.

II. Experiment

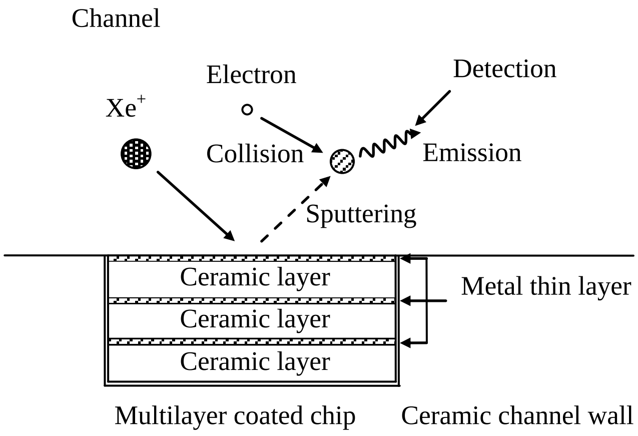

Figure 1. Principle of erosion rate measurement method using multilayer coating chip.

A. Principle of 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, which is usually boron nitride (BN).

When the Hall thruster operates, ion sputtering erodes the embedded chip and the surrounding channel wall. Then 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. Therefore the channel wall erosion rate can be calculable from the intervals of periodic peaks of emission signals.

Erosion rate measurements can be conducted much more quickly by using this method, within less than half an hour. Furthermore, the emission intensity fluctuation has no influence on accuracy, which is a significant advantage over other real time erosion rate measurement methods. Moreover, this method has fine spacial resolution because of the small multilayer coated chips.

B. Erosion rate Distribution Measurement

Erosion rate distribution measurement by multilayer coating method can be accelerated by using more than one kind of chip at the same time. 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 erosion rate distribution measurements. In this way, erosion rate distribution measurement can be accelerated greatly, and moreover, the required number of channel wall ceramics with holes for chips can be reduced. Chips of two kinds were used for this study.

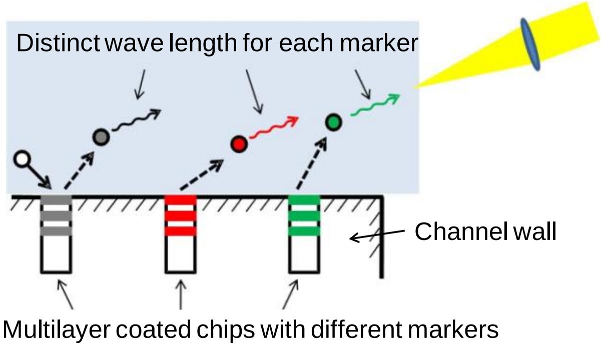

Figure 2. Diagram of erosion rate distribution measurement.

C. Multilayer Coated Chip

The marker metal material was chosen as follows.

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

$$\kappa_t = S\frac{M_t}{\rho_t} \tag{1}$$

$$v = N_i\kappa_t \tag{2}$$

Material which has high volumetric erosion rate is appropriate for marker. High κ_t means high number density of marker material in the channel, which makes emission of marker atom easier to detect. Table 1 shows the volumetric sputter yield κ_t against Xe^+ beam of BN and several candidates of marker material.[7, 8] Taking the availability of the material into consideration, Ag was mainly used as marker metal in this study, whereas Pd was also used during the erosion rate distribution measurement.

Several versions of multilayer coating chips were used in this study, and fig. 3 shows a typical one. There were minor thickness changes, but the basic structure remained the same. The shape of chip is column and its diameter is 1 mm. The base material of the chips is Al (A5052). Three layers each for marker and BN were coated alternately. The top layer was BN in order not to interfere the thruster operation. The respective thicknesses of BN and marker layers were 164 nm and 45 nm. However, in order to distinguish the emission of bottom marker layer from those of the other layers, the bottom layer of marker were coated 3 times thicker than others.

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. Figure 4 is a photograph of the coating process. The device on the right top is the ion source, and the substance at the bottom is the coating material. Table 2 shows the operation conditions of the coating device.

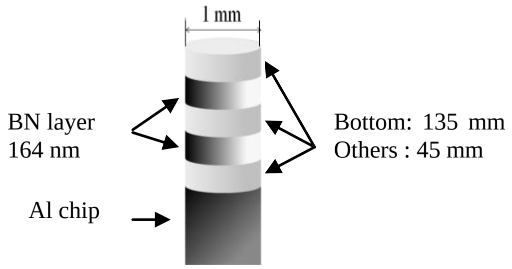

Figure 3. Schematic of multilayer coating chip.

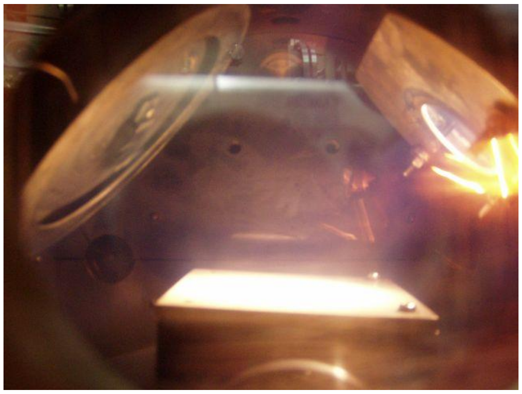

Figure 4. Ion beam sputtering coating device.

Table 1. Volumetric sputter yield.

Material	$\kappa_{t,}$ cc/mol		
Ion energy, eV.	100	200	300
Ag	4.11	10.8	18.5
Cu	1.86	5.64	9.21
Pt	1.73	6.55	11.4
Au	1.63	10.2	18.7
Fe	0.43	2.06	3.83
BN	0.48	1.54	1.93

Table 2. Operation condition of coating device.

Parameter	Value
Working gas	Argon
Flow rate	1.5 sccm
Acceleration voltage	800 V
Ambient pressure	2.8×10^{-3} Pa

D. Hall Thruster

Figure 5 shows the 1 kW class magnetic layer type Hall thruster developed at The University of Tokyo. The inner and outer diameters of the acceleration channel are, respectively, 48 mm and 62 mm. The channel length is 21-mm long and the wall material is BN.

Multilayer coated chips were lined up in the axial direction. The presence of multilayer coating chips did not affect the Hall thruster operation. The operation parameters of the Hall thruster were the same, irrespective of whether the chips were embedded or not.

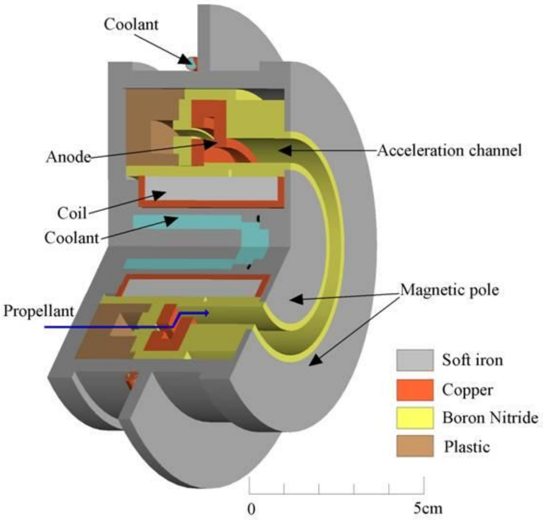

Figure 5. UT magnetic layer type Hall thruster.

E. Optical system

Figure 6 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 (328.1 nm and 338.3 nm) and Xe II (336.7 nm) were measured simultaneously using the same spectrometer. During the erosion rate distribution measurement, the emission history of Pd (340.5 nm) was also observed at the same time. Table 3 shows the spectrometer measurement setting. The dead time of the spectrometer was negligible.

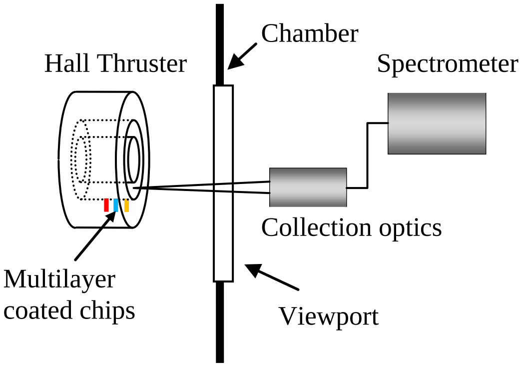

Figure 6. Schematic of optical system.

Table 3. Measurement condition of Optical system.

Parameter	Value
Sampling rate	1 Hz
Exposure time	1 s
Wave length range	323 nm to 343 nm
Wave length resolution	0.02 nm

III. Results and Discussion

A. Measurement result

Figure 7 presents 2 samples of observed time varying emission intensity of marker metal (Ag). The emission intensity is normalized by the highest value for convenience. In both samples, 3 peaks of emission were observed corresponding to 3 marker layers of the chip. The third peak has largest area because that the bottom marker layer was coated three times thicker than others in order for identification. The emission of marker metal did not drop to zero even after all marker layers were worn out. This is caused by the noise of emission spectroscopy, and can be neglected as far as the peaks can be identified.

However, there are 2 problems left. First, the observed emission peaks gradually became dull with time. This is believed to be resulted from that the erosion rate on the chip is not uniform. As a result, if the erosion rate is too slow compared with the thickness of coated layers, the calculated channel wall reduction rate will be inaccurate. On the other hand, if the erosion rate is too fast compared with the thickness of coated layers, the emission peaks will be merged together. This also reduce the accuracy of the measurement. Therefore, the thickness of layers should be chosen appropriately depending on the measuring erosion rate.

The second problem is that despite the top layer of multilayer coating chip is BN, the emission of marker always starts at the moment of Hall thruster starts. This is supposed to be caused by the unsteady operation of the Hall thruster during the ignition. In fact, we ignite the Hall thruster by lowering coil current, and adjust the operation condition after the ignition. Therefore, only 2nd and 3rd peaks of emission were used for channel wall reduction rate calculation in this study. However, the reason of very high erosion rate (more than 100 nm/s) at the moment of ignition remains to be an open question.

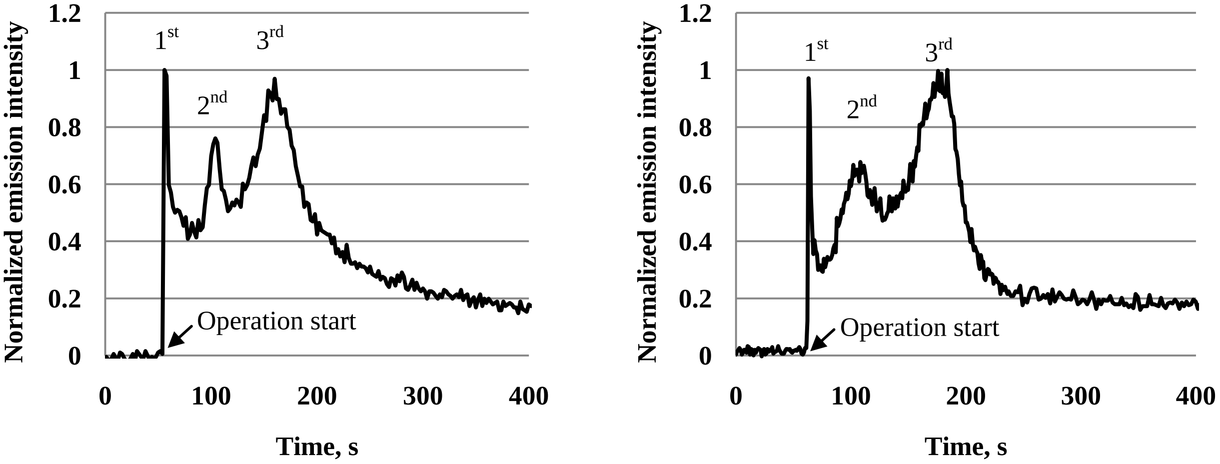

Figure 7. Time vary emission intensity of marker metal.

B. Data analysis

Fitting function was used in order to determine the center of emission peaks without ambiguity. The used fitting function is shown as follows.

$$I \cong \frac{A}{\sqrt{(t-C)^2+B}} \tag{3}$$

Where *A*, *B*, and *C* are arbitrary constants, and *C* is the center of peak. The observed emission history was fitted by the summation of this function. Figure 8 presents the fitting of emission history. As the graph shows, the fitting function agreed with the experiment result very well. The channel wall reduction rate can be calculated as follows:

$$v \cong \frac{T_{\mathrm{BN}} + T_{\mathrm{M}} \cdot \frac{\kappa_{\mathrm{M}}}{\kappa_{\mathrm{BN}}}}{\Delta t} \tag{4}$$

Where T is thickness of layers, κ is volumetric sputtering yield taken from table 1, Δt is the interval of emission peaks obtained from marker emission history. Subscript BN and M respectively show ceramic layer and marker layer. Since the second term of numerator is much smaller than the first term, the marker layer's thickness is not important.

As mentioned in the optical system, in order to monitor the plasma condition, the emission history of Xe II (336.7 nm) was also observed during the measurement. Figure 9 presents emission histories of Xe II with different number of chips embedded into the channel wall. The emission intensity was normalized by the highest value. The graph shows that first; the number of chips has little influence on the thruster operation. Secondly, the thruster operation is steady except the moment of ignition. This result supports the reliability of multilayer coating method.

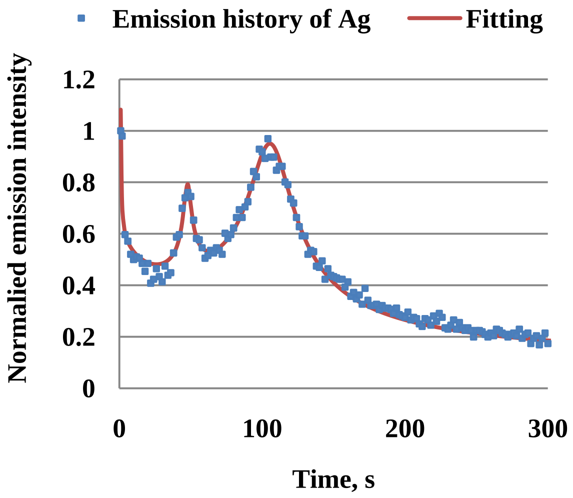

Figure 8. Fitting of emission history.

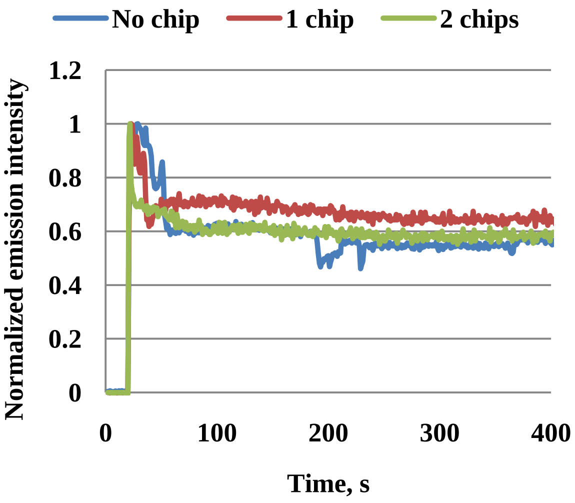

Figure 9. Emission history of Xe II.

C. Magnetic flux density and erosion rate

The relation of magnetic flux density and channel wall erosion rate was measured by multilayer coating method. Figure 10 shows the placement of the chip. In practice, BN channel wall with a 1 mm diameter hole was prepared, and multilayer coating chip using Ag as marker was inserted into the hole. The chip was fixed and insulated from the magnetic circuit. Table 4 shows the operation condition of the Hall thruster. The selected mass flow rate was relatively low compared with the optimum value (2.72 mg/s, anode efficiency ~ 45%).

Figure 11 shows the measurement result. Blue line shows channel wall reduction rate (erosion rate) in nm/s. Every 2 or 3 measurements were conducted for all measurement points, and the error bars indicate their standard deviations. The magnetic flux density is calculated values at the center of channel exit. In practice, 1.0 A coil current corresponds to 15 mT. The graph shows that the erosion rate is very high in low magnetic field range, and then takes minimum value at around 14 mT, and increases again in high magnetic field range. The measurement results in low magnetic field range are inaccurate since the erosion rate is too high so the emission peaks merged together. Multilayer coating chips with much thicker layers are needed for accurate measurement of this range.

The corresponding anode efficiencies were measured separately, and shown on the same figure by red line. As the graph shows, the low erosion rate range does not agree with the high anode efficiency range. The erosion rate at 21 mT is almost 2 times higher than that at 14 mT, which is not a negligible difference. There is no concrete evidence or explanation for the physical background of this tendency, so it will be our future work.

In order to verify the measurement result of multilayer coating method, measurement under the same condition by conventional emission spectroscopy was conducted by Yokota and Kaneko. The result is presented by figure 12. Three lines show the erosion rate with different discharge voltages. The results of 2 different methods cannot be simply compared with each other, since there are 2 major differences between them. First, conventional emission spectroscopy measures the relative value of erosion rate, whereas multilayer coating method measures the absolute value. Secondly, emission spectroscopy measures the total amount of erosion, whereas multilayer coating method measures the erosion rate at a specific point. However, the tendencies of the results of 2 methods agree well with each other. This fact supports the correctness of multilayer coating method. The comparison with long time operation is anticipated in the future.

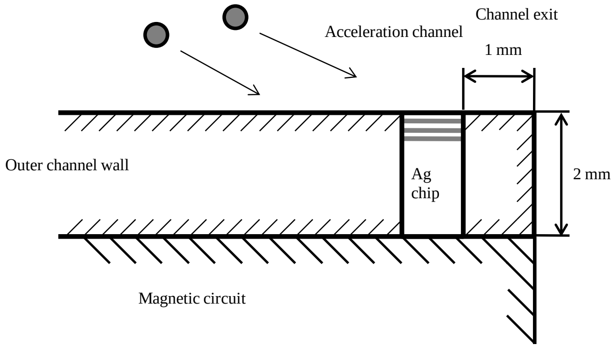

Figure 10. **Schematic of multilayer coating chip placement.**

Table 4. **Operation condition of Hall thruster.**

Parameter	Value
Propellant gas	Xenon
Mass flow rate	1.36 mg/s
Discharge voltage	300 V
Discharge current	1.1 to 2.0 A
Magnetic flux density	10.5 to 21 mT
Ambient pressure	3.7×10^{-3} Pa

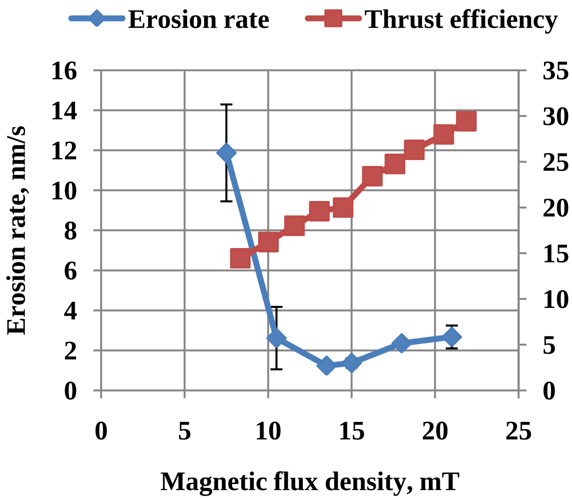

Figure 11. **Magnetic flux density and erosion rate (Multilayer coating method).**

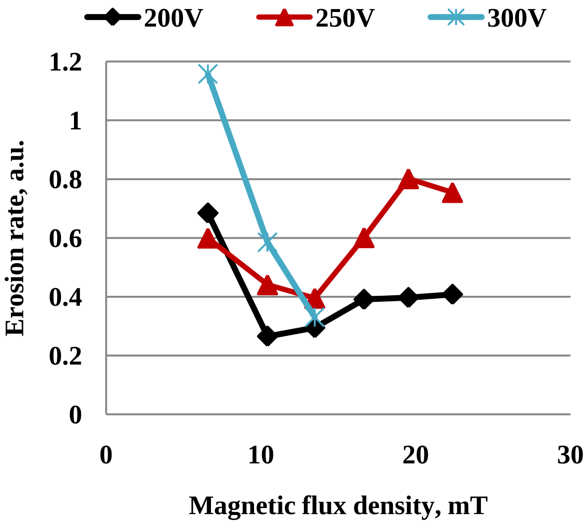

Figure 12. **Magnetic flux density and erosion rate (Emission spectroscopy).**

D. Erosion rate axial distribution measurement

Axial distribution of channel wall reduction rate was measured by multilayer coating method. Figure 13 shows the placement of chips. In order to accelerate the measurement, erosion rate at 2 different points were measured simultaneously by using 2 kinds of chips (Ag and Pd). In practice we prepared 2 channel wall ceramics with 2 holes in different places, and inserted each kind of chip into the holes. The chip using Pd as marker was placed near the exit, since the emission of Pd was expected to be weaker than that of Ag. The operation condition is presented by table 5.

Figure 14 shows the measurement result. Only one measurement was conducted for each point. The x axis of the graph presents the center of the chip's distance from the channel exit plane. The graph shows that first, at the channel exit, the erosion rate is higher than that of magnetic field measurement (2.4 nm/s compared with 1.4 nm/s) due to increased mass flow rate (2.04 mg/s compared with 1.36 mg/s). Secondly, the erosion rate is highest at the exit of channel wall, and monotonically decreases toward the anode side. The volumetric erosion rate within the measured region can be calculated by integration, and the result is 1.2 mm^3/s. These results are reasonable compared with previous studies.[4,9]

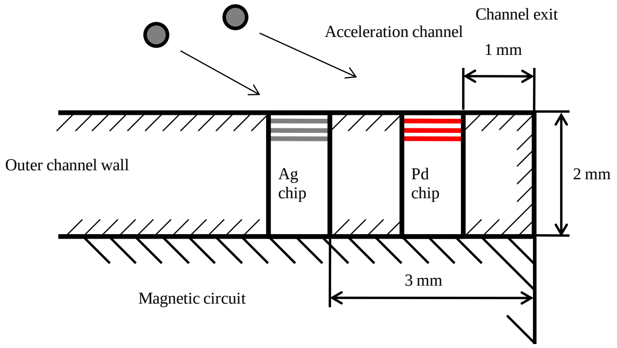

Figure 13. Schematic of multilayer coating chips placement.

Table 5. Operation condition of Hall thruster.

Parameter	Value
Propellant gas	Xenon
Mass flow rate	2.04 mg/s
Discharge voltage	300 V
Discharge current	2.3 A
Magnetic flux density	15 mT
Ambient pressure	5.6×10^{-3} Pa

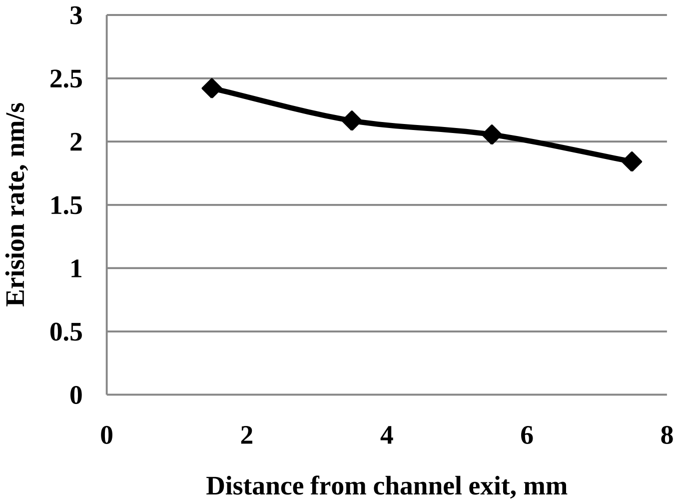

Figure 14. Axial erosion rate distribution.

IV. Conclusion

A new channel wall reduction rate measurement method – multilayer coating method was introduced in this study. This method combines advantages of conventional methods, and has three major merits: short measurement time, direct erosion rate measurement, and fine spatial resolution.

To demonstrate these merits, first, the relation between magnetic flux density and erosion rate was examined by this new method. The measurement result was verified by comparing with that of the conventional emission spectroscopy. Secondly, the axial distribution of channel wall reduction rate was measured by multilayer coating method. The measured distribution and integrated volumetric erosion rate was reasonable compared with previous studies.

However, the reason of the observed very high erosion rate at the moment of ignition and the reason of mismatches between maximum thrust efficiency range and minimum erosion range are not resolved yet. These problems would be our future works. In addition, the improvement of the measurement accuracy and verification by long time operation are also required.

V. References

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