ABSTRACT

Two types of microwave ion thrusters using a resonant cavity have been investigated to develop high performance ion thrusters. The one is using ordinary microwave discharge, and the other is using ECR (Electron Cyclotron Resonance) discharge. Microwaves of 2.45 GHz are introduced into a cavity and give a strong electric field for gas breakdown. The electric field pattern on the inner cavity wall was measured by a microcoax probe. The maximum electric field of 25.7 kV/m was obtained at a forward power of 185 W with a reentrant coaxial cavity. Due to this strong electric field, the minimum mass flow rate sustaining ordinary microwave discharge decreased to 6 sccm. Furthermore, ion beam was electrostatically extracted from generated microwave plasma by two multiaperture grids. In ordinary microwave discharge mode, the maximum ion beam current of 119 mA was obtained for argon plasma, and the estimated ion production cost and mass utilization efficiency were 769 eV and 12.7 %, respectively. In ECR discharge mode, the maximum mass utilization efficiency of 18.7 % was achieved at a beam current of 75 mA.

INTRODUCTION

Electrodeless microwave discharge has many attractive characteristics as follows; (1) no electrodes, i.e., no erosion; (2) electrical breakdown in gases is easy for the strong electric field; (3) simple configuration. Therefore it has been applied to excitation sources for gaseous electronics studies, such as light and laser sources, and to plasma and ion materials processing, such as plasma assisted chemical vapor deposition (CVD), reactive ion and plasma etching, ion implantation and ion milling etc. In present paper, microwave ion sources are studied to develop high performance ion thrusters in space.
Figures 1 and 2 show the cross section and overview photograph, respectively, of the microwave ion thruster using ordinary microwave discharge. The thruster consists of a resonant cavity, a disk-shaped quartz discharge chamber in the front wall of the resonant cavity, which is 80 mm in inner diameter, and two grids extraction system. The resonant cavity has a cylindrical outer conductor, center conductor and sliding wall. The outer conductor is 120 mm in inner diameter; the center conductor 80 mm in outer diameter. The sliding wall and center conductor are adjustable to provide variable cavity length (L) and gap length (D), as shown in Fig.3. Two types of cavity resonance mode can be realized in this cavity. The one is cylindrical cavity mode (L=D), and the other is reentrant coaxial cavity mode (L>D). The resonant condition of the cavity is adjusted by moving the sliding wall and center conductor. On cylindrical cavity mode, the TM_{011} mode is excited up in the cavity at the theoretical cavity length of 98 mm. Figure 4 shows the theoretical electromagnetic field distribution of TM_{011} mode. This mode has the maximum electric field in the center of the bottom plate of the cavity.

The microwave ion thruster using ECR discharge is shown in Fig.5. This thruster consists of the cylindrical resonant cavity, the disk-shaped quartz discharge chamber, the beam extraction grids and five rings of samarium-cobalt magnets. Two of the magnet rings are inserted in the discharge chamber and three of them settled on the bottom plate of the discharge chamber. Each of the ring magnet is composed of 5x5x10 mm magnet blocks; These magnet rings produce a ring-cusp magnetic field in the chamber. Figure 6 shows the arrangement of the magnet rings. ECR condition of 2.45 GHz needs a magnetic field intensity of 875 Gauss as drawn in Fig.6.
Microwaves are introduced into the resonant cavity by direct connection between a rectangular waveguide and the cavity. Figure 7 represents the microwave transmission system. Microwave powers of 2.45 GHz and maximum 1 kW are generated by a magnetron. The impedance of the transmission line is matched to that of the cavity plasma load as well as possible by three-cavity stub tuning. Forward power (P_f) and reflected power (P_r) are measured by a directional coupler connected with a power monitor; absorbed power of P_i ( = P_f - P_r ) and coupling efficiency of η ( = P_i / P_f ) are calculated.

The ion thrusters are equipped with the multiaperture two grids extraction system, which are made of stainless steel plate of 0.5 mm thickness. Ions are extracted from plasma by these grids. The first grid of a screen grid has 2.0 mm - diameter holes and 43 % transparency. The second grid of an accelerator grid has 1.2 mm - diameter holes and 19.1 % transparency. The gap between the grids is 0.9 mm.

Electric fields on the inner wall of the cavity are measured with a microcoax electromagnetic probe so as to infer the electromagnetic field pattern excited in the cavity. The probe signals are rectified and displayed on a digital oscilloscope. The detected signals, which is proportional to the square of electric field, are calibrated by comparison of the signals measured on the inner wall of a rectangular wave guide with their theoretical electric fields. Detected positions of the cavity are shown in Fig. 8.

Figure 9 shows the experimental system with a microwave ion thruster fixed on a flange of a vacuum tank. In order to extract ion beam, two high voltages are applied between the grids. Total extracted beam current I_b is estimated from the currents through the screen and accelerator grids, I_s and I_a, respectively. Beam profiles are measured with a Faraday-cup, which is located at 5 cm downstream of the grids, moving across the beam. The Faraday-cup have 2 mm diameter of a current limiting aperture and a repeller grid for suppressing secondary electron emission.

EXPERIMENTAL RESULTS AND DISCUSSION

ION THRUSTER USING ORDINARY MICROWAVE DISCHARGE

Figure 10a shows the coupling efficiency vs cavity length characteristics for argon at a forward power of 185 W in cylindrical cavity mode. The coupling efficiency has a maximum peak at the cavity length of 98 mm. This cavity length agrees with the theoretical cavity length of TM_{012}-resonance mode as sketched in Fig. 4. In Fig.10a, the coupling efficiency has another peak in 200 mm of the cavity length. This cavity length corresponds to the TM_{021}-mode cavity length. The gradual curve of the characteristics from 130 to 150 mm is ascribed to a generation of high-order mode, such as TE_{123} and TE_{213} mode. As the mass flow rate decreases, the peak characteristics of TM_{012}, TM_{021} and TE_{213} mode appears more clearly, as shown in Fig.10b.
Figure 11 shows the coupling efficiency dependence of mass flow rate at a forward power of 184 W. The minimum mass flow rate, with which the discharge can be sustained, is 10 sccm at cylindrical cavity mode. However, moving and adjusting the center conductor as a reentrant coaxial cavity, the minimum mass flow rate of discharge decreases to 6 sccm. The reentrant coaxial cavity mode is useful at mass flow rate ranges from 6 to 10 sccm.

Figure 12 shows the electric field patterns on the bottom plate of the cavity at the same forward power of 184 W without plasma. The cavity length of 98 mm corresponds to cylindrical cavity mode, and 90, 80 and 70 mm to coaxial reentrant cavity mode. The distribution of axial electric field on the bottom plate with the cavity length of 98 mm, which corresponds to TM_{011} resonance mode, has an antinode with axisymmetry and 10.2 kV/m of maximum electric field strength at the center. On the other hand, the electric field on the bottom plate of the cavity increases with decreasing cavity length in reentrant coaxial cavity mode. At a cavity length of 70 mm and a gap length of 35 mm, the maximum electric field strength of 25.7 kV/m is obtained at the center, and it is about 2.5 times as large as that with cylindrical cavity mode. Electric breakdown at the lowest mass flow rate of 6 sccm is easy for the strong electric field of the reentrant coaxial cavity, although the strong electric field does not give a high coupling efficiency compared with in cylindrical cavity mode.
From the above experimental results, the operating point of beam extraction is decided. Figure 13 shows the beam extraction characteristics of cylindrical cavity mode for various forward powers at a mass flow rate of 14 sccm. The ion beam current increases with the total extraction voltage and forward power. The maximum beam current of 119 mA is achieved with a forward power of 184 W at a total acceleration voltage of 750 V. Figure 14 shows the beam extraction characteristics of cylindrical cavity mode for various mass flow rates. Both the ion beam currents at mass flow rates of 14 and 18 sccm are almost equal in this experiment. Ion production cost and mass utilization efficiency are estimated from obtained data. The lowest ion production cost of 769 eV and highest mass utilization efficiency of 12.7% were achieved for cylindrical cavity mode. Figure 15 shows the typical output of an ion beam profile detected by a Faraday cup moving across the beam. Ion beam profile has the maximum current density at the center of the beam. The divergent angle of the beam is determined from the beam edge, which is defined as 5% height of the peak of the beam profile. In Fig.15, the ion beam diverges at an angle of 28.4° at the total acceleration voltage of 700 V.

In order to reduce neutral loss, the cavity excitation of reentrant coaxial mode was examined at a low mass flow rate. The reentrant coaxial cavity was capable to operating at a low mass flow rate of 6 sccm, as shown in Fig.11. Figure 16 shows the ion beam current characteristics with reentrant coaxial cavity mode. The extracted ion beam current is much smaller than that with cylindrical cavity mode, and a low mass utilization efficiency of 7.9% is obtained. Accordingly, the cavity excitation of reentrant mode is not efficient in this experiment.
ION THRUSTER USING ECR DISCHARGE

Microwave ion thruster using ordinary microwave discharge was not capable of giving a good efficiency. In order to reduce mass flow rate and achieve high mass utilization efficiency, ECR discharge is very useful. Figure 17 shows the coupling efficiency dependence of mass flow rate using ECR discharge, as shown in Fig.5. ECR discharge can be maintained at the lowest mass flow rate of 3 sccm and gives a high coupling efficiency over 90% at a low forward power of 99 W.

Figure 18 shows the ion beam current characteristics at a mass flow rate of 6 sccm. In this experiment, the maximum ion beam current of 75 mA is obtained at a forward power of 99 W. From these data, the maximum mass utilization efficiency of 18.7% are achieved with the ion thruster using ECR discharge, though the ion production cost is very high.

SUMMARY AND CONCLUSIONS

The ion thruster using the resonant cavity were investigated to obtain the fundamental operational characteristics and to understand the discharge features for development of high-performance ion thrusters.

In the ion thruster using ordinary microwave discharge, the following results were obtained:

1) The coupling efficiency had a maximum for the theoretical cavity length of TM011 mode in the cylindrical cavity.
2) Although the minimum mass flow rate of discharge was 10 sccm in cylindrical cavity mode, it decreased to 6 sccm in reentrant coaxial cavity mode.
3) More than 25.7 kV/m of electric field was achieved with the reentrant coaxial cavity, and electric breakdown is easy for the strong electric field even at a low mass flow rate of 6 sccm.
4) In cylindrical cavity mode, the maximum beam current of 119 mA was obtained for a forward power of 184 W at a total acceleration voltage of 750 V.
5) The divergent angle of the beam was 28.4° for a forward power of 184 W at a total acceleration voltage of 700 V in cylindrical cavity mode.

In the ion thruster using ECR discharge, the following results were obtained:

6) The minimum mass flow rate of discharge decreased to 3 sccm at a forward power of 99 W.
7) The highest mass utilization efficiency 18.7% was achieved at a mass flow rate of 6 sccm.
REFERENCES


