Study of 2.5~10cm Size Microwave Discharge Ion Thruster

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Several experimental and numerical simulation results for the development of miniature microwave discharge ion thrusters have been reported. The important points to improve the performance of the ion thruster are the shape of the antenna for microwave emission and the magnetic configuration in its thruster head. The extracted ion beam current of 12mA is obtained in conditions of input 2.45GHz microwave power of 8W and propellant (xenon) flow rate of 0.2 sccm with a star type antenna. A numerical simulation code coupling the particle-in-cell method and the finite difference time domain method was used to know plasma behavior in the discharge chamber of an ion thruster.

Key Words: Electric Propulsion, Ion Thruster, Microwave Discharge, Antenna, Magnetic Configuration

1. Introduction

The need of satellites has recently increased since artificial satellites offer important services such as weather forecasts, satellite communication and broadcasting, and car navigation by GPS. In the space application, small satellites are expected to be used as they have the advantages of flexibility, short development periods, and low costs^{1,2)}.

A series of small-scale satellites are expected to be applicable instead of traditional large-scale satellites for reducing launch costs and risks. The trend toward needs of small spacecraft requires mN class micro thrusters. A miniature microwave discharge ion thruster is one of the answers for the requirement and has advanced features of a high specific impulse (more than 3000s) and high propellant utilization efficiency. In the thruster, the plasma is produced by ionizing propellant with high-energy electrons accelerated by microwave in a magnetic field. As the thruster utilizes no cathodes for

plasma production, it is relieved from the cathode heater failure resulting from the degradation of cathodes, while the thruster needs only one microwave power supply to produce plasma. These features will assure long operating life and high reliability of the thruster³⁾.

In this work, several experimental and numerical simulation results have been reported for the development of miniature microwave discharge ion thrusters in the size of 2.5~10cm^{4,5)}. The ion thruster utilizing microwave discharge plasma has been fabricated and tested to clarify its performance dependence on the shapes of its microwave emitting antennas and the magnetic configuration in its discharge chambers. A numerical simulation code has also been developed to know plasma behavior in a discharge chamber of the ion thruster.

2. Experiment

2.1. Experimental Apparatus

Fig. 1 shows an experimental apparatus for the

Fig. 1. Schematic diagram of the experimental setup for the micro ion thruster.

performance tests, which comprises a cylindrical vacuum chamber (inner diameter of 60 cm and length of 100 cm), a 2.45GHz microwave power supply, a thruster head, and vacuum pumps of a 300 l/s turbo molecular pump and a 2000 l/s cryopump. Microwave power is supplied from the power source through a coaxial cable to the thruster head. The length of the coaxial cable was adjusted for impedance matching between the power source and the thruster head. The ultimate pressure and the pressure at Xe gas (as propellant) flow rate of 0.2 sccm in the vacuum chamber were 1×10^{-4} Pa and 1.6×10^{-3} Pa respectively.

2.2. Thruster Head

The basic structure of a microwave discharge ion thruster head is shown in Fig. 2. A magnetic field is generated in the discharge chamber with Sm-Co permanent magnets (surface magnetic flux density of 0.3T). The magnetic flux density of the electron cyclotron resonance (ECR) layer is 0.0875T for 2.45GHz microwave. An antenna is used for microwave radiation into the discharge chamber. Microwave discharge plasma is generated and confined in the cusp magnetic field produced by the permanent magnets. The magnetic field strength and configuration are arranged by choosing the number of the magnets. Ions are extracted and accelerated by two electrostatic grids, a screen grid and an acceleration grid. They are made of molybdenum. The distance of the grids is 0.25mm. The discharge chamber and the screen grid are biased 1500V toward the ground. The acceleration grid is biased to -300V (Fig.1).

2.3. Performance Tests

The tests were carried out to clarify the thruster performance dependence on antenna shapes and magnetic configurations in the discharge chamber^{6,7)}. The ion beam currents emitted from the miniature thruster were

Fig. 2. Schematic of a miniature microwave discharge ion thruster head.

Fig. 3. Antennas for microwave radiation, (a) L-type antenna, (b) star, (c) disk, (d) punched disk.

measured under several experimental conditions. Fig. 3 shows antennas used in the performance test. Four types of antennas (L-type antenna, star, disk, and punched disk) were examined. The performance dependence on the internal magnetic configuration in the discharge chamber was investigated with the number of permanent magnets of $N_{\text{mag}}=10 \sim 16$ by using a square type discharge chamber. These tests are all under experimental conditions of the Xe gas flow rate of 0.2~0.4 sccm.

3. Results and Discussion

3.1. Performance dependence on antenna shapes

The extracted ion beam currents at $\dot{m}=0.2\text{sccm}$ or 0.4sccm for the four types of the antennas such as L-type antenna, star, disk, and punched disk are shown in Fig. 4⁶⁾. All antennas are made of molybdenum. The ion beam current by the star-type antenna is more than 1.4 times larger than those by other antennas. As the plasma is produced at the high electric field region near the antenna, the star-type antenna generates wider high-density plasma regions than others, therefore it produces higher ion beam current. Between the disk-type antenna and punched disk, the ion beam current by the punched disk is larger than that by the disk antenna because of area effect. Ion recombination on the antenna surface brings loss of plasma. The punched disk-type antenna has the advantage of the smaller planar dimension than the disk one. The star type antenna is suitable for the miniature microwave discharge ion thruster because of these results. The star type antenna has, moreover, the advantage of good plasma ignition as well as the high density plasma production.

3.2. Performance dependence on magnetic field

Fig. 5 shows the dependence of ion beam current on magnetic configurations under incident microwave power

Fig. 4. Dependence of ion beam current on antenna shape, (a) $\dot{m}=0.2\text{sccm}$ of Xe, (b) 0.4sccm .

of 8W and Xe mass flow rate of 0.2sccm⁷⁾. There is an optimum magnetic configuration because of the peak value of $N_{\text{mag}}=12$. This is due to the tradeoff between the surface recombination of ions on the wall of the discharge chamber and the microwave-plasma coupling. Though the magnetic confinement is improved with increasing magnetic field strength (N_{mag}), the coupling of plasma with microwaves becomes worse due to the increase in the distance between the antenna and the ECR layer^{8~10)}. Internal magnetic configurations of the discharge chamber by numerical calculation are shown in Fig.6. The plasma was not generated beyond $N_{\text{mag}}=16$, because the distance between the antenna and ECR layer is too far away (see Fig. 6). The plasma was suitably produced with the magnetic configuration of $N_{\text{mag}}=12$.

4. Numerical Simulation of Internal Plasma

To investigate the plasma behaviors in the discharge chamber of the miniature microwave discharge ion thruster numerically, a simulation code by coupling the particle-in-cell (PIC) method and the finite difference time domain (FDTD) method has been developed^{8~10)}.

Fig. 5. Dependence of ion beam current on magnetic configuration ($\dot{m}=0.2\text{sccm}$, $P_i=8\text{W}$).

Fig. 6. Magnetic configuration for each N_{mag} (a) $N_{\text{mag}}=10$, (b) 12, (c) 14, (d) 16.

Adopting the code has advantages that the collision process and the distribution function of electrons are treated by the PIC method while absorption of microwave in plasma is analyzed by the FDTD method. The interaction between microwave and electrons is observed using the code. A calculation model is given in Fig.7.

Fig. 8 shows an electron trajectory derived by the simulation code. The electron at its initial position moves toward the front yoke and is reflected near the front yoke. Then, the electron moves toward the back yoke. The electron crosses the ECR layer and it is then reflected again near the back yoke. The electron is confined within the magnetic mirror.

Fig. 9 shows magnetic configurations (the permanent magnet numbers of 9~11) and the distribution of incremental electron energy through the ECR layer. The incremental energy decreases although the number of magnets increases. With an increase in the number of

Fig. 7. Calculation model of miniature microwave discharge ion thruster.

Fig. 8. Computed electron trajectory.

Fig. 9. Incremental electron energy through the ECR layer.

magnets, the strength of the electric field on the ECR layer decreases because of the increase in the distance between the ECR layer and the antenna (see Fig.9). On the other hand, the wall surface loss of plasma generally decreases with increase of the magnetic field strength. The simulation result shows that the magnetic configuration in the discharge chamber must be optimized in consideration of the electron behavior to improve thruster performance.

5. Conclusions

Experiment and numerical simulation results have been reported to develop miniature microwave discharge ion thrusters (the size of 2.5~10cm). The obtained results are as follows.

- 1) The star type antenna is suitable for a miniature microwave discharge ion thruster since it provides good plasma ignition and high density plasma.
- 2) There is an optimum magnetic configuration due to the tradeoff between the surface recombination of plasma and the microwave-plasma coupling. We must choose an internal magnetic configuration in consideration of plasma ignition and confinement of plasma.
- 3) The simulation code coupling the PIC method and the FDTD method has been developed to investigate plasma behavior in a discharge chamber. The code simulates an electron trajectory in a cusped magnetic field and indicates that there is a tradeoff between the surface recombination of plasma on the chamber wall and the microwave-plasma coupling for high density plasma generation.

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