J. Jpn. Soc. Microgravity Appl. Vol. 28 No. 2 2011 (S23–S26)

8th Japan-China-Korea Workshop on Microgravity Sciences
for Asian Microgravity Pre-Symposium

Experiments of Fine-Particle Plasma using Planar Magnetron Plasma System

Yasuaki HAYASHI, Yohei MIZOBATA and Kazuo TAKAHASHI

Abstract

A planar magnetron plasma system was developed for the research of fine particle plasmas. Fine particles were successfully confined above the center of loop of magnetron plasma forming a three-dimensional structure against the gravity. Distribution of plasma density and potential measured by the method of Langmuir probe suggests that the horizontal confinement of fine particles is caused by electrostatic force, while the vertical lifting is not caused by the force but by another mechanism. A small cubic magnetron plasmas system, which has a potential to drive fine particles to the center of plasma, was developed for microgravity experiments.

1. Introduction

Fine-particle plasmas, which mean highly negative-charged fine particles suspended in a plasma, exhibit a variety of physical phenomena, e. g., crystal structures, the phase transition and critical phenomena [1-3]. Analyses of the physical phenomena by the motion and position of each particle will bring a new analytical method in material science. However, fine particles usually form the simple hexagonal structure in a plasma under gravity because they are not suspended in a plasma but sink in the sheath forming particle strings in the vertical direction. Hence the microgravity condition is required for the analyses in material science using three-dimensional (3D) arrangement of fine-particles in a plasma.

Another problem for the formation of a large-area 3D crystal structure is the appearance of a void around the center of plasma under microgravity as well as gravity. In the conventional systems of fine particle plasma experiment, simple parallel-plate RF (radio frequency) plasma systems were used with a ring to confine particles in the horizontal direction. However, in the system, fine particles often form a void, probably caused by outward ion drag force from the center of plasma.

In order to control forces acting on fine particles in a plasma, we developed a system of planar magnetron RF plasma [4,5]. In this system, electrons are confined by $\boldsymbol{E}\times\boldsymbol{B}$ drift just above the surface of RF electrode, and a loop of plasma is generated close to the RF electrode. In the loop-shaped plasma, fine particles were confined toward the horizontal center and pushed upward against gravity.

In this paper, forces driving fine particles in a planar magnetron plasma are analyzed by plasma diagnostics using the method of Langmuir probe.

2. Experimental

The developed planar magnetron plasma system for the research of fine particle plasmas is shown in **Fig. 1**. A 13.56 MHz RF electrode is put in the lower part in a vacuum chamber. A counter ground electrode is not provided, but the upper flange of the chamber, which is put 15 cm above the RF electrode, and chamber wall act as a grounded electrode. Eight pieces of strong neodymium-base permanent magnets are octagonally put on an iron plate in the RF electrode. An iron ring is put inside of the octagonally arranged magnets on the iron plate. They form magnetic fields parallel to the surface of the RF electrode. The maximum parallel magnetic flux density is 1400 G at the radial position of 38 mm from the center of electrode surface.

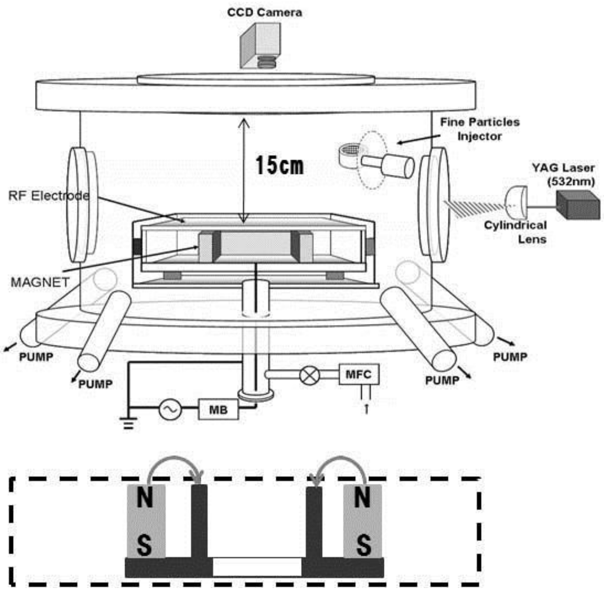

Fig. 1 Schematic diagram of the planar magnetron plasma system.

Department of Electronics, Faculty of Engineering and Design, Kyoto Institute of Technology, Matsugasaki, Sakyo-ku, Kyoto, Japan
(E-mail: hayashiy@kit.ac.jp)

A high density plasma is generated due to electrons circularly confined by the ***E***×***B*** drift.

The distribution and arrangement of fine particles were observed by laser light scattering at 532 nm in wavelength using CCD video cameras provided at upper and side positions through view windows.

Plasma density and potential were measured using a Langmuir probe. The probe tip was a tungsten wire 5 mm in length and 0.3 mm in diameter. It was set perpendicular to the surface of RF electrode. Plasma density was determined by the ion saturation current. A reference probe is also prepared in the system of Langmuir probe to correct the DC (direct current) shift of the measurement.

The experimental conditions were as follows: discharge gas, argon; RF discharge power, 2 to 10 W; gas pressure, 100 Pa; and fine particles, divinylbenzene spherical particles of 6.5 microns in diameter.

3. Results and Discussion

Figure 2 shows the oblique view of generated planar magnetron plasma with an RF power of 4 W. The generation of a loop of optical emission by planar magnetron plasma is confirmed on the surface of RF electrode. It should be noted that a disc-shaped region of dimmer optical emission is observed inside the loop. The diameter of the region is about 25 mm. Fine particles were suspended and confined mainly in this central region.

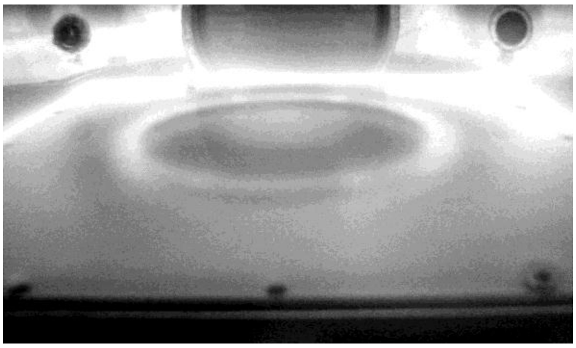

Fig. 2 Oblique view of planar magnetron plasma.

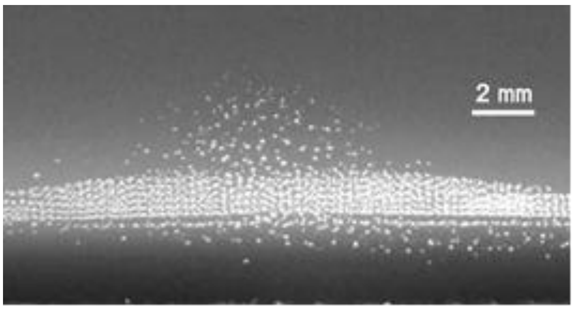

Fig. 3 Fine particles suspended above the center of RF electrode. The surface of RF electrode is at the lower end of the picture.

Figure 3 shows the arrangement of fine particles observed through a side view window with an RF power of 2 W. Fine particles were distributed in the region of dimmer optical emission. It should be noted that fine particles do not form vertical string in the lower region, which is usually observed in the sheath in a conventional RF plasma [6,7], even with such larger particles. Moreover, fine particles are observed to arrange in horizontal layers at the height more than 2.8 mm above the RF electrode. Such arrangement is generated by compressive force in the direction perpendicular to the layers. Because vertical strings of fine particles are formed by plasma wake in the sheath [6], it is recognized that the sheath exists lower than 2.8 mm from RF electrode. Some particles are observed to be levitated above the center of group of fine particles in **Fig. 3**. The results imply the existence of upward force.

In order to analyze the force acting on fine particles, plasma diagnostics by the method of Langmuir probe was carried out. The horizontal distributions of plasma density and plasma potential was measured with the center of probe tip 6 mm above the surface of RF electrode (**Fig. 4**). Because the length of probe is 5 mm, the measurement was practically carried out in the range of height between 3.5 to 8.5 mm in a plasma. Plasma density and potential decreased with the increase of radial distance to 17 mm from the horizontal center of electrode as shown in **Fig. 4**. Because fine particles are negatively charged

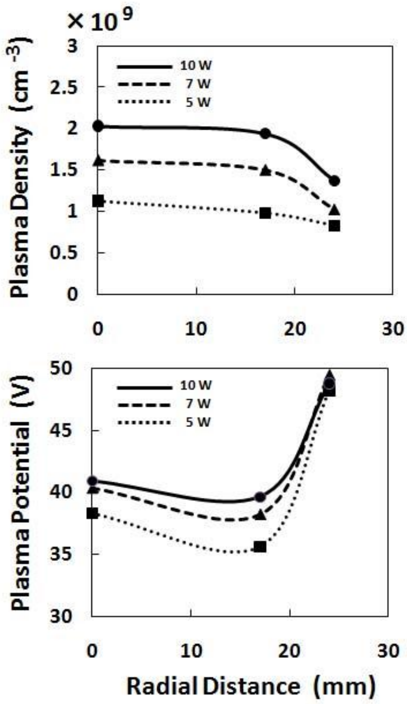

Fig. 4 Horizontal distribution of plasma density and plasma potential. Radial distance is measured from electrode center.

in a plasma, they are confined around above the center of RF electrode, where potential is higher than that in surroundings. In this case, ion drag force acts on fine particles outwards because plasma density above the center is higher than that in surroundings.

Figure 5 shows the distributions of plasma density and plasma potential in vertical direction above the horizontal center of electrode surface. The height of measurement is defined at the longitudinal center of probe tip. Plasma density increases with the increase of height to 10 mm, while plasma potential does not have the tendency of increase. It is suggested that the fine particles were pushed upwards not by electrostatic force, i. e., potential increase, but by another force.

Consequently, fine particles are driven toward above the center of electrode surface by horizontal electrostatic force, while they are not driven upwards by the force against gravity. They are lifted upwards by another force under the force balance with gravity. If gravitational force is removed from forces acting on them, it is expected that they are suspended at higher position.

In order to apply planar magnetron plasma to microgravity experiments, a cubic magnetron plasma system was developed as shown in **Fig. 6**. The side length of cubic vacuum chamber is 15 cm. Eight pieces of permanent magnets and an iron ring are put on an iron plate with the same configuration and

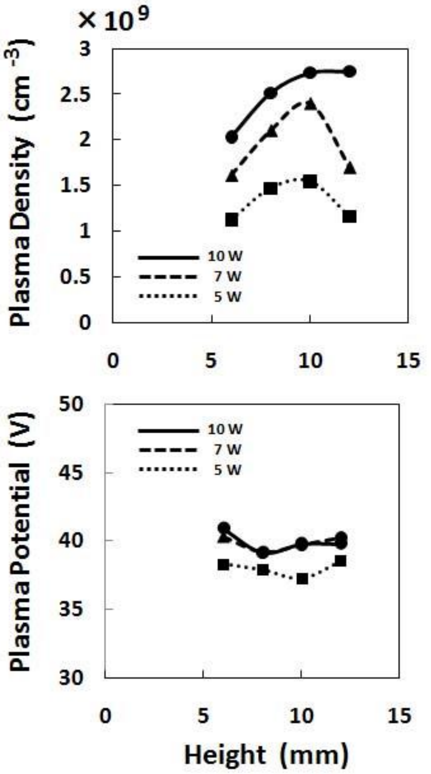

Fig. 5 Vertical distribution of plasma density and plasma potential. Height is measured from electrode surface.

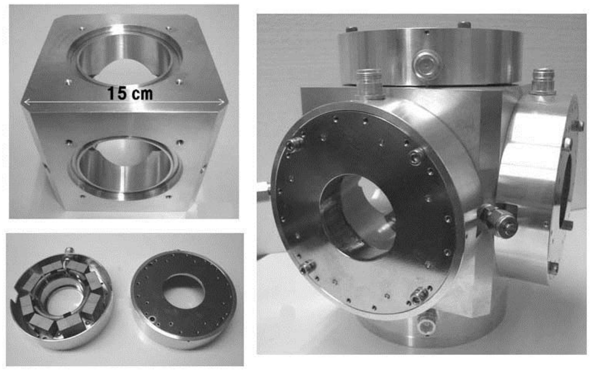

Fig. 6 Cubic magnetron plasma system for microgravity experiments of fine particle plasma.

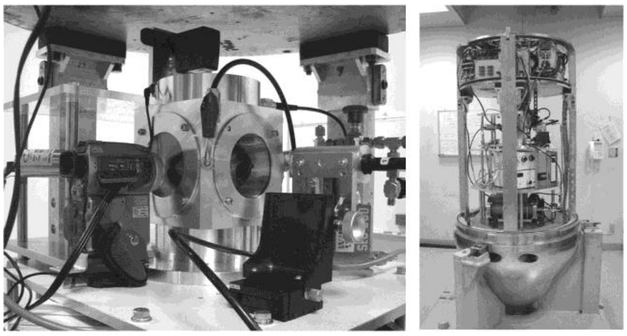

Fig. 7 Cubic magnetron plasma system in drop experiment capsule.

dimensions as that in the above-mentioned experiment. A cupper ring, which is put on a nonmagnetic spacing ring set between eight magnets and an iron ring, plays a role of RF electrode outside. 6 units of magnetron electrode are able to be attached on each side of the cubic chamber. Fine particles are expected to be driven toward the center of the cubic chamber under microgravity. The arrangement of fine particles can be observed through a view window, because the center of magnetron electrode has a hole.

The cubic magnetron plasma system was installed in a capsule of drop experiment at MGLAB in Japan as shown in **Fig. 7**. In this case, two units of magnetron electrode were attached on the top and bottom sides. The behavior of fine particles was successfully recorded by a CCD video camera and is on the way of analysis.

4. Summary

A new experimental system, a planar magnetron plasma system, was developed for the research of fine particle plasmas. Fine particles were successfully confined around above the center of loop of magnetron plasma forming a three-dimensional structure. It seems that there exist forces driving fine particles toward the horizontal center and pushing upwards against gravity. Distribution of plasma density and potential measured by the method of Langmuir probe suggests that the horizontal confinement of fine particles is caused by electrostatic force, while the vertical lifting is not caused by the force but by another mechanism. The developed cubic magnetron plasma system has a potential to drive fine particles to the center of plasma.

Acknowledgement

Authors would like to thank emeritus professor of Tohoku university, N. Sato, and emeritus professor of Kyushu university, Y. Watanabe for helpful discussion.

References

1) Y. Hayashi and K. Tachibana, Jpn. J. Appl. Phys. **33** (1994) L804; J. H. Chu and Lin I, Phys. Rev. Lett. **72** (1994) 4009; H. Thomas *et. al.*, Phys. Rev. Lett. **73** (1994) 652.
2) S. A. Khrapak, G. Morfill, A. Ivlev, H. Thomas, D. Beysens, B. Zappoli, V. Fortov, A. Lipaev and V. Molotkov, Phys. Rev. Lett. **96** (2006) 015001.
3) H. Totsuji, Phys. Plasmas, **15** (2008) 072111.
4) Y. Hayashi, Y. Mizobata and K. Takahashi, Plasma Fusion Res. SER. **8** (2009) 298.
5) Y. Hayashi, M. Imano, Y. Mizobata and K. Takahashi, Plasma Sources Sci. Technol. **19** (2010) 034019.
6) F. Melandso and J. Goree, Phys. Rev. E, **52** (1995) 5312.
7) K. Takahashi, T. Oishi, K. Shimomai, Y. Hayashi and S. Nishino, Phys. Rev. E, **58** (1998) 7805.

(Received 20 Oct. 2010; Accepted 10 Jun. 2011)