Evaluation method of fine particle charge and measurement of spatial electric field in Ar plasma using optical tweezers method

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1. Introduction

There is a strong need for processing of materials at nanometer scale to allow the continuous miniaturization of devices. Plasma processing is mainly used to manufacture these devices. The measurement of sheath electric field in a microscopic space is an important issue for optimizing plasma processing of materials. For example, small changes and fluctuations in the electric field have a significant impact on etching and deposition into high aspect ratio micro-/nano-structure.

A lot of different techniques have been developed for the measurement of electric fields in plasmas. Electric field can be derived from local measurements of the plasma potential using Langmuir probes or emissive probe [1]. However, these probes are highly invasive since typical probe size is a few mm. As a result, all of these probing techniques have in common the change of chemical reaction on the probe as well as the disturbance of the plasma. One of non-invasive technique is the measurements by laser, e.g. laser-induced fluorescence (LIF) -dip spectroscopy [2]. The sensitive detection limit of 3 V/cm with spatial resolution of several hundreds of micrometers obtained by LIF-dip allowed the measurement in the Ar plasma [2]. However, few reports have been published on sensitive measurements of electric field distributions with high spatial resolution on the micrometer scale.

One technique to manipulate micro-particles are optical traps, often named as optical tweezers [3]. Therefore, in this study, we have investigated such sensitive measurements of strength and fluctuation of electric field in plasma using optically trapped fine particles by a laser-tweezer technique. Moreover, we have evaluated charge of fine particle by new method based optical tweezers.

2. Method

A plasma reaction vessel with a quartz window on the top and a sapphire window on the bottom was used in the experiments. A perforated metal ground electrode was placed in the center of the vessel, and a ring-shaped electrode with an inner diameter was placed on the bottom of the vessel. A high-frequency voltage of 13.56 MHz was applied between the electrodes to generate plasma in the vessel. When an acrylic particle of 20μm in diameter (mass density: 1.20 g/cm^3) was introduced into plasma, it was suspended near the plasma/sheath boundary. A single particle was trapped with the laser tweezers (λ = 1064nm) and moved horizontally with the laser light until the particle was de-trapped. At the levitation position of a fine particle, the electrostatic force and the laser light force on the particle were balanced by the gravity. The force of the laser on the particle F_{ray} was obtained from a ray optical model [4], and a particle charge Q_p was deduced from Orbit Motion Limited model with ion collision [5]. Each z- and r- force balance equations are as follows, z-direction: $mg = Q_pE_z + F_{ray\_z}$ and r-direction: $F_{ray\_r} = Q_pE_r$.

Eventually, we deduced vertical electric field strengths E_z from these derivations. Moreover, strengths and fluctuations of horizontal electric fields E_r were deduced by deriving horizontal force balance. As the results, we obtained 2D profiles of electric field vector with a high spatial resolution in micrometer scale.

Here, the charge of fine particle is very important parameter to deduce the electric field strength using this method. Therefore, we developed new method to evacuate the charge fine particle in plasma by measuring the distance between two microparticles using optical tweezers, aiming to improve the accuracy of electric field measurements.

3. Results and Discussion

We measured the levitation positions of the laser-trapped fine particle in Ar plasma for each laser power and each position to get information of E_r and E_z. These results of electric fields were agreed with the numerical result by PIC-MCC model. Furthermore, the experimentally obtained charge number of the fine particles was in close agreement with the Orbital Motion Limited (OML) theory incorporating ion-neutral collisions[6].

The details will be reported at the conference.

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References

[1] T. Lho, N. Hershkowitz and G.H. Kim, Rev. Sci. Instrum. 71, 403 (2000).
[2] T. Takizawa, K. Sasaki, and A. Kono, Appl. Phys. Lett. 84, 185 (2005).
[3] A. Ashkin, Biophys. J. 61 (1992) 569.
[4] Philip H. Jones, et al., Optical Tweezers Principles and Applications, 22 (Cambridge university press, 2015).
[5] G. Paeva, Sheath phenomena in dusty plasmas, (Technische Universiteit Eindhoven, 2005).
[6] S. A. Khrapak, et al., Phys. Rev. E 72 (2005) 016406.