New Evaluation Method of Charge of a Microparticle in Ar Plasma Using Optical Tweezers

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Abstract: We developed a new experimental method for determining the charge of a microparticle suspended in plasma using optical tweezers. The magnitude of the charge of the microparticle obtained from this method closely matched the values predicted by the ion-collision OML theory.

1. Introduction

With the advancement of nanostructure formation and the 3D integration of semiconductor devices, the demand for ultra-precise nano-processing techniques grounded in a comprehensive understanding of plasma processes has been increasing[1]. Therefore, controlling fluctuations in plasma parameters within micro-scale spaces on the μm and nm scales in plasma processes is crucial. Currently, research on electric field strength measurement and its fluctuations with μm-scale resolution in plasma is limited. To address this challenge, we have developed a method for measuring electric field strength with a high spatial resolution on the μm scale using microparticles in plasma that are optically trapped by optical tweezers [2] as probes. Since the charge of the microparticles significantly affects electric field measurements, an accurate measurement method is important. Therefore, in this study, we propose a novel method to derive the charge of a microparticle in plasma by measuring the distance between two microparticles using optical tweezers, aiming at improving the accuracy of electric field measurements.

2. Methods

To generate Ar plasma, an rf voltage with a frequency 13.56MHz was applied between the powered ring electrode and the ground planar electrode. A fine particle (PMMA, a diameter of 15 μm) was injected into the plasma. A microparticle in plasma acquired a negative charge, it levitated and remained confined at the center of the apparatus. We investigated the dependence of the particle charge on RF power (2–7 W) (not shown in this abstract) and gas pressure (20–100 Pa).

To determine the charge of a microparticle in plasma, two experimental procedures were performed. In the first experiment, a single microparticle was introduced into the plasma and optically trapped using optical tweezers. The trapped microparticle was then gradually displaced outward from the center of the apparatus. By tracking its position during this process, the force exerted by the background electric field was measured. In the second experiment, two microparticles were introduced into the plasma. One microparticle was optically trapped and displaced outward from the center, while the other remained untrapped. The position of the untrapped microparticle and the interparticle distance were recorded. From the above two experiments, the charge of a microparticle Q is expressed as $Q = d\sqrt{4\pi\varepsilon_0 F_{ray\_r}}$. By integrating the results from both experiments, the charge of a microparticle in plasma can be determined.

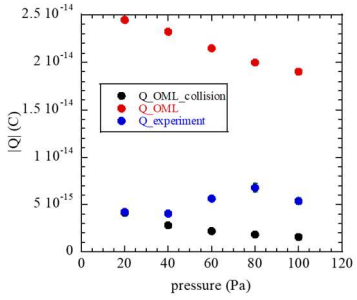

Fig. 1. Comparison of the experimental charge values with the OML theory and ion-collision OML theory values (RF power: 5W).

3. Results and Discussion

Figure 1 shows the pressure dependence of the charge of microparticle obtained by new experimental method. For instance, at a pressure of 40 Pa and an RF power of 5W, the charge of a microparticle was deduced to be $Q = -4.06 \times 10^{-15}$ C. The magnitude of the measured charge is consistent with the value predicted by the ion-collision OML theory[3]. The charge tends to increase with the pressure. This suggests that the change in charge is due to variations in plasma density and temperature associated with increasing the pressure. The pressure range in this study's experimental conditions (p = 20–100 Pa) corresponds to a regime where ion collisions play a significant role to the charge. Therefore, our method is useful to obtain the charge information both with and without such ion collision effects. Further details will be presented at the conference.

Acknowledgement

This work was partly supported by JSPS KAKENHI (Grant No. JP24H00205 and No. JP23K03368) and JST ASPIRE (Grant No. 1234505).

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