Plasma etching of single fine particle trapped in Ar plasma by optical tweezers

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Abstract. Physical and chemical interactions between plasmas and nano-featured surfaces are one important issue in the plasma processing. Here we optically trap single fine particle levitated at plasma/sheath boundary with an infrared laser to realize in-situ analysis of such interactions. We have measured time evolution of the diameter of the single fine particle in Ar plasma. The trapped particle was etched at an etching rate of 1 nm/min in Ar plasma. We also obtained a Raman peak at around 2950 cm⁻¹ corresponding to C-H bonds in the single fine particle in Ar plasma. The results open a new possibility to observe directly interactions between plasma and single fine particle.

1. Introduction

Plasma processing plays a central role in nanotechnology and is widely employed for producing large scale integration, nano-films, graphene, nanoparticles, and so on [1-28]. Spatial and temporal fluctuation of plasma parameters, such as electron density, electron energy distribution, kinetic energy of ions impinging on surfaces, and radical density, is an important cause of fluctuations of size, structure, and properties of nano-materials and nano-devices produced by plasma processing. However, relation between these two fluctuations has not been clarified yet. To clarify the relation, we have studied physical and chemical interactions between plasmas and fine particles suspended in plasmas [16-28]. Conventional approach of in-situ observation of such interactions is ensemble average observation, namely, interactions between plasmas and many fine particles are observed. Observation of single fine particle in plasmas offers an alternative way of studying physical and chemical interactions between plasmas and fine particles and quantitative evaluation of forces exerted on a fine particle. Here we report interactions between plasma and “single fine particle” trapped by using optical tweezers, namely, a single-beam gradient laser trap.

2. Experimental

Figure 1 shows a schematic diagram of the experimental apparatus. Experiments were carried out with
a radio frequency low pressure plasma reactor, which was a stainless steel one of 38 mm in inner
diameter and 31 mm in inner height and had two quartz windows: the top window was employed to
observe fine particles in plasmas with a CCD camera and the bottom one was employed to irradiate
Nd: YAG 1064-nm laser light to a fine particle for optically tweezing it [29-31]. A powered
ring-electrode of 10 and 25 mm in inner and outer diameter was set at the bottom of the reactor and a
grounded stainless steel mesh electrode of 25 mm in diameter was placed at 9 mm above the bottom of
the reactor. Ar plasmas were generated at a total pressure of 40-100 Pa by applying 13.56MHz voltage.
The discharge power was 1.9-2.9 W. For the pressure of 100 Pa and the discharge power of 2.9W, the
peak-to-peak discharge voltage and self-bias DC voltage were 300 V and -55 V, respectively.

Particles injected into the plasmas were monodisperse methyl methacrylate-polymer (PMMA)
spheres of 1.2 g/cm³ and 10 μm in diameter. Particles injected into the plasmas were charged
negatively and were suspended at the plasma/sheath boundary at the center of the powered electrode
due to the balance between gravitational force and electrostatic force exerted on the particles. An
optical trap is formed by tightly focusing a laser beam with an objective lens (Sigma, NIR Plan APO
LMPAL-50-NIR) of high numerical aperture (NA=0.8). A dielectric particle near the focus
experiences a force due to the transfer of momentum from the scattering of incident photons [16-18].
The resulting optical force is decomposed into two components: (1) a scattering force, in the direction
of light propagation and (2) a gradient force, in the direction of the spatial light gradient. At the focal
point of the irradiated laser light, one of the fine particles can be optically trapped in plasmas where
electrostatic force, ion drag force, neutral drag force, and gravity were exerted on the fine particle. We
observed the fine particle with a CCD camera (Sentech, STC-TC202USB-AT) with a spatial
resolution of 1600×1200 pixels and 88 nm/pixel at a maximum frame rate of 15.32 fps.

We also carried out in-situ Raman spectroscopy of single fine particle in Ar plasma with an
exposure time of 0.1 s. The Raman signal was accumulated over 30 times to improve the signal to
noise ratio.

Figure 1. Schematic diagram of plasma reactor, optical tweezers, and in-situ Raman spectrometer.
3. Results and discussion

We succeeded in trapping and manipulating a single fine particle levitated at plasma/sheath boundary in plasmas by controlling precisely the focal point and power of the laser light. Figure 2 shows a typical image of the trapped fine particle obtained with the CCD camera. The particle was trapped around plasma/sheath boundary, at 0.5 mm above the powered electrode. The fine particle followed the shift of the focal point, and then it was released just after turning off the laser irradiation. Radiation pressure acts on the fine particle to the direction of the focal point due to the difference of refractive index between the fine particle and Ar gas. The electron temperature and electron density for 100 Pa, 2.9 W discharge plasma are 1.9 eV and 1.7x10^9 cm^-3. The corresponding charge accumulated on a fine particle is \(-7300e\). Since the gravitational force is 6.1 (pN), the electric field needed for the counter balance to the gravitational force is 52 V/cm. A trapping laser power of 0.1 W can provide an optical trapping force of 100 pN, which is significantly large compared with the other forces exerted on the fine particle.

Figure 3 shows time evolution of the diameter of a fine particle trapped optically in Ar plasma. We observed a gradual decrease in the diameter of trapped fine particle due to interactions between the trapped particle surface and the Ar plasma. The diameter decreases linearly with time due to sputter etching at an etching rate of 1 nm/min. Since the ion flux to the fine particle is \(6\times10^{15} \text{ cm}^{-2}\text{s}^{-1}\), the apparent sputtering yield deduced from the etching rate is 0.8, being high compared with 0.1 in the previous reports [32]. This high sputtering yield may be attributed to a synergetic effect of simultaneous irradiation of ions and VUV photons from Ar plasma [19].

![Figure 2. A typical image of single fine particle of 10 µm in diameter, trapped optically in Ar plasma.](image)

![Figure 3. Time evolution of diameter of a fine particle trapped optically in Ar plasma.](image)
Figure 4 shows Raman spectrum of single acrylic fine particle in Ar plasma. There is a peak at around 2950 cm\(^{-1}\) corresponding to C-H bonds in the single fine particle.

The results in figures 3 and 4 open a new possibility to observe directly interactions between plasma and single fine particle.

4. Conclusions

Single fine particle was trapped in Ar plasma by using the optical tweezers with the IR laser. We demonstrated in-situ observation of interactions between plasmas and the trapped fine particle. The trapped fine particle was etched at an etching rate of 1 nm/min in Ar plasma. We also obtained a Raman peak at around 2950 cm\(^{-1}\) corresponding to C-H bonds in the single fine particle in Ar plasma.

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