Position fluctuation of a fine particle optically trapped in Ar plasma

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We have analysed position fluctuation of a single fine particle trapped with laser optical tweezers in Ar plasma. We have deduced the characteristic length of the position fluctuation that gives information on interactions between plasmas and the trapped particle. The trapped particle can be employed as a local probe for measurements of spatiotemporal fluctuations of plasma parameters.

1. Introduction

Plasma processing plays a central role in nanotechnology and is widely employed for producing nanodevices and nanomaterials such as LSI, graphene, carbon nanotube, nanoparticles, and so on [1-3]. Spatiotemporal fluctuations of plasma parameters is an important cause of fluctuations of size, structure, and properties of nanodevices and nanomaterials produced by plasma processing. So far relation between these two fluctuations has not been clarified yet. Traditional approach of in-situ observation of such interactions is ensemble average observation. For instance, interactions between plasmas and many fine particles have been observed [4-10]. Observation of a 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 [11, 12]. Here we report interactions between plasma and “a single fine particle” trapped by optical tweezers, that is to say, a single-beam gradient laser trap [12].

2. Experimental

Figure 1 shows a schematic diagram of the experimental setup. Experiments were carried out with a radio frequency low pressure plasma reactor, where we set two quartz windows as top and bottom flanges. The light from a lamp was irradiated from the top window to observe fine particles. The bottom window was employed to irradiate Nd: YAG 1064-nm laser light to trap optically a fine particle and observe it with a CCD camera.

A powered stainless steel 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 100 Pa by applying 13.56MHz, 600 V peak to peak voltage.

The injected fine particles were monodisperse methyl methacrylate-polymer spheres of 10 μm in diameter. First, fine particles were injected into the reactor and were suspended around the plasma/sheath boundary near the powered electrode. Then, we irradiated the laser light from the bottom through an objective lens which has a long working distance of 3.8 mm. One of the fine particles was optically trapped near the focal point. Eventually we measured spatial profile of optical transmittance of the optically trapped fine particle. For the transmittance measurements, the frame rate of CCD camera is 30 fps.

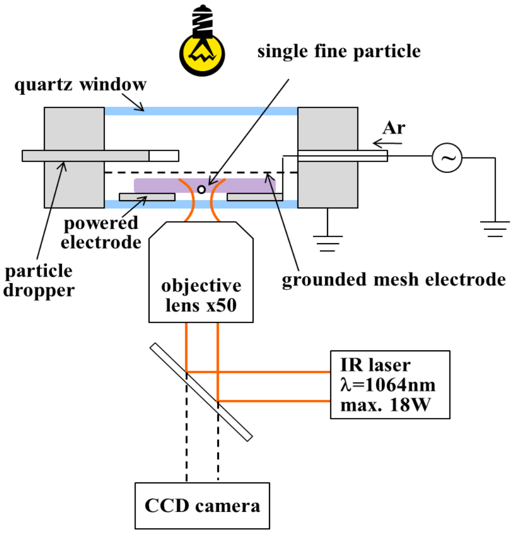

Figure 1. Schematic diagram of plasma reactor and optical tweezers.

3. Results and discussion

Figure 2 shows spatial profiles of optical transmittance of (a) a particle put on the bottom window without plasma and (b) a particle trapped in plasma. Low transmittance region corresponds to the fine particle. For the particle put on the bottom, the transmittance has sharp edges at 12 and 23 μm, whereas for the particle trapped in plasma the transmittance has blurred edges. These results show clearly that the particle without plasma stays still, while the trapped particle moves in the potential

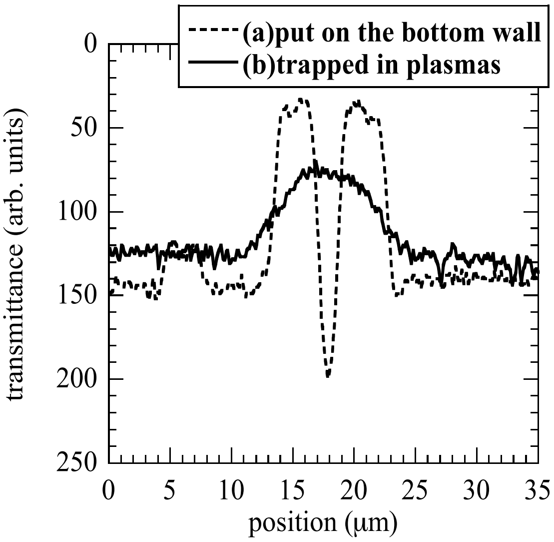

Figure 2. Spatial profiles of optical transmittance of (a) a particle set on the bottom without plasma and (b) a particle trapped in plasma.

well of the optical trap by driving force due to interactions between plasmas and the particle.

Based on the results, we analyse the position fluctuation of the trapped particle. We assume that the particle moves as a Brownian particle. The probability density function $\rho_x(x)$ of position of a particle trapped in the potential well of one dimensional harmonic oscillator is given by a Gaussian distribution:

$$\rho_X(x) = A\exp\left(-\frac{x^2}{L^2}\right) \qquad (1)$$

where A is a constant, L is a characteristic length of the position fluctuation given by

$$L = \sqrt{\frac{2k_bT}{k}} \qquad (2)$$

where k_b is Boltzmann constant, and T is the translational temperature of the particle. Employing A and L as fitting parameters, the spatial profile of transmittance for the trapped particle is obtained using that for the particle without plasma and eq. (1). Figure 3 shows the theoretical transmittance for L^2= 10 μm^2 together with the experimental one. The theoretical curve matches well the experimental one. The characteristic length L of the position fluctuation is 3.16 μm which contains onformation on the spring constant k of one-dimensional harmonic oscillator and translational temperature of the particle as shown in eq. (2). Langevin equation of the trapped particle is given by

$$m\frac{dV}{dt} = -kx - m\nu v + \delta \qquad (3)$$

where v is the velocity of the particle, m is the mass of the particle, k is the spring constant of the trapped potential, *ν* is the viscosity coefficient, and δ expresses a force fluctuation. From motion of un-

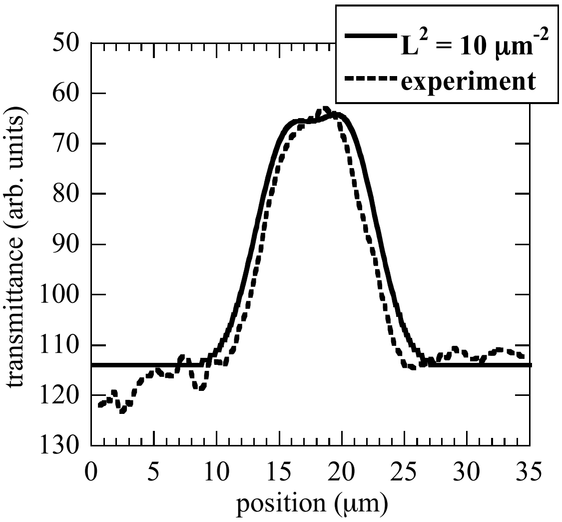

Figure 3. Theoretical transmittance (solid line) and experimental transmittance (broken line).

trapped particles the kinetic temperature of particles deduced is 910K. Then k is 2.51×10^{-3} pN/μm. From the k value and eq. (3), the fluctuation of plasma parameters can be deduced.

4. Conclusion

We have analysed the position fluctuation of a single fine particle optically trapped in Ar plasma and have obtained the characteristic length of the fluctuation. The trapped particle can be employed as a local probe for spatiotemporal fluctuations of the plasma parameters.

Acknowledgement

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