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Transport of dust particles in multi-frequency capacitively coupled radio frequency discharges
多重周波数容量結合型ＲＦ放電を用いたダストの輸送制御

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The levitation position of micrometer-sized dust particles is controlled by the phase angle θ of 13.56 and 27.12MHz waveforms applied to a power electrode in geometrically symmetric capacitively coupled radio frequency discharges via a Electrically Asymmetry Effect. Here, dc self bias voltage is a linear function of the phase angle θ even in a geometrically symmetric CCRF plasmas, and controlled by the phase angle θ. We succeeded in transportation of dust particles toward a upper ground electrode by abruptly changing phase angle θ from 90 to 0 degrees.

1. Introduction

In plasmas, dust particles are negatively charged up to form so-called ``plasma crystals" under the strong Coulomb interaction among the dust particles [1-4]. There have been many experiments on the dust particles and various interesting features of dust-particle plasma have been clarified [5]. Moreover, dust-particle composite films have a great potential for many application such as catalysts, sensors, solar cell, Large scale Integration. It is an essential issue to understand and control the collective motion of dust particles levitating in plasmas in order to fabricate dust particle composite films [6]. Particularly, the control of an electrostatic field is quite important, because the charged particles are sensitive to the electric field in plasma, and new dust-particle structures such as vortices and void are generated and controlled by an appropriate potential structure. In this study, we propose a novel method for the transport of dust particles to substrates using the Electrical Asymmetry effect (EAE) in dual-frequency capacitively rf discharges [7,8].

2. Experiment

Experiments were carried out using a CCRF discharge reactor, as shown in Fig. 1. The powered and grounded electrodes of 100 mm diameter were placed at a distance of 20 mm in the reactor. Plasma was generated by applying the phase locked 100 peak-to-peak voltage (V_{pp}) of 13.56 MHz and 27.12 MHz generated using two synchronized function generators.

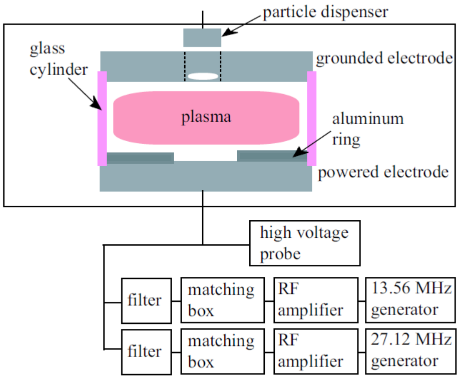

Figure 1. Experimental setup.

Here, the voltage waveform ϕ is given by

$$\phi(t) = \phi_0[\cos(2\pi f t + \theta) + \cos(4\pi f t)], \qquad (1)$$

where ϕ_0 and θ are the amplitude of each harmonic and the variable phase angle between the harmonics, respectively, and f is a fundamental frequency of 13.56 MHz. The pressure was sustained at 1-10 Pa in an argon atmosphere. A filter blocked the other harmonic behind each matching box, and the two voltage waveforms were added and applied to the powered electrode behind the filters. The plasmas were shielded from the outer grounded chamber walls by a glass cylinder, which realize geometrically symmetric CCRF discharges. The temperature of the reactor wall was kept at room temperature to eliminate the influence of thermophoretic force exerted on dust particles. SiO_2 dust particles of 1.5 μm in size were injected into the reactor using a particle dispenser above the upper grounded electrode. For suppressing agglomeration of dust particles a wire cloth mesh having holes of 38 mm in size was equipped with the particle dispenser. An aluminum ring having a hole of 60 mm in diameter was set on the lower powered electrode to trap dust particles in the center above the ring. Dust particles injected were observed using a two dimensional Laser Light Scattering method [6, 9]. A laser sheet of 660 mW at 532 nm was passed parallel to the surface of the two electrodes. The height and width of the laser sheet was 20 mm and 1 mm, respectively. The intensity of light scattered by particles was detected at right angles with an ICCD camera or a CCD camera equipped with an interference filter.

Figure 2 shows dc self-bias as a function of the phase angle θ. We can clearly observe that the dc self bias is controlled by changing the phase angle θ. Figure 3 shows dust-particle levitation positions as a function of the phase angle θ. A dust particle position almost linearly decreases with increasing the phase angle θ, and quite sensitive to the dc self bias.

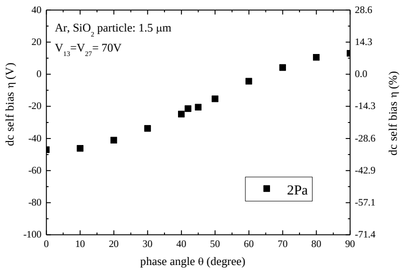

Fig.2. DC self bias as a function of phase angle θ.

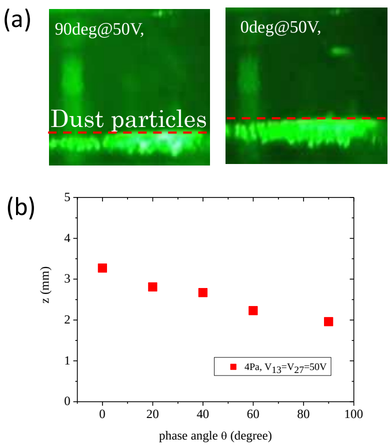

Fig.3. (a) Images of dust particles levitating in ion sheath. (b) A levitation position of dust particles as a function of phase angle θ.

Finally, we succeeded in the transportation of dust particle toward upper a ground electrode by abruptly changing phase angle θ from 90 to 0 degrees as shown in Fig. 4. This method is quite effective to control dust-particle motion in plasma.

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