MEASUREMENT OF NEGATIVELY CHARGED DUST BY USING AN ELECTRIC PROBE IN LARGE RF HELIUM PLASMAS

TECHNICAL NOTE

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We investigated charged dust and its effect on RF plasma by using a planar electric probe in a large-scale device. In background plasmas, the particle density is 10^8 to 10^9 cm^{-3} and the electron temperature is 2 to 4 eV. When dust is contained in plasma, it is negatively charged by electrons attached to the dust. The charged dust density and the charge were calculated by comparing dusty helium plasma to pure helium plasma. Depending on the increase in the amount of dust, the charged dust density increases with the decrease in the charge due to depletion of the electrons in the background plasma. The results show that the charge changes the interactions between the dust and particles in the background plasma.

KEYWORDS: *dusty plasma, negatively charged dust, charged potential*

Note: Some figures in this technical note may be in color only in the electronic version.

I. INTRODUCTION

Dust grains in the range from nanometer to micrometer are produced by factors such as plasmas species, and interactions between plasmas and device walls.[1–7] Dust produced has been observed by various detectors such as the scanning electron microscope (SEM), the modified capacitive diaphragm gauge (CDG), and laser scattering detection in semiconductor and fusion devices.[3–7] This dust has a number of negative effects on background plasma including plasma contamination, loss of energy, and yield in devices.[3–8] When dust is contained in plasma, it is charged by collecting electron and/or ions. The charged dusts are then trapped and levitated by the sheath potential.[8–12] The movements of the charged dust vary by plasma source, electric field, and the amount of dust.[7–9] This dust is considered as a potential source for "killer defects" on the etching layer in semiconductor fields. Also, dust is potentially harmful because they can include radioactive sources that must be removed in fusion devices.[3–6] On the other hand, dust has advantages in new materials and their applications.[1–2] Specially, their advantages are in the fundamental physics of plasmas such as ion acoustic wave, sheath thickness, plasma oscillation, and their waves.[7–13] Dust can be positively charged by photon emission and thermionic radiation[8,10] but is typically negatively charged by electron attachment whose thermal velocities are fast compared to that of the heavier ions.[7–15] The negatively charged dust can play the role of negative ions, which affect the quasi-neutrality of the background plasma.[7,14,15] Interactions between dust and particles have been theoretically studied, both as ions absorbed and/or trapped

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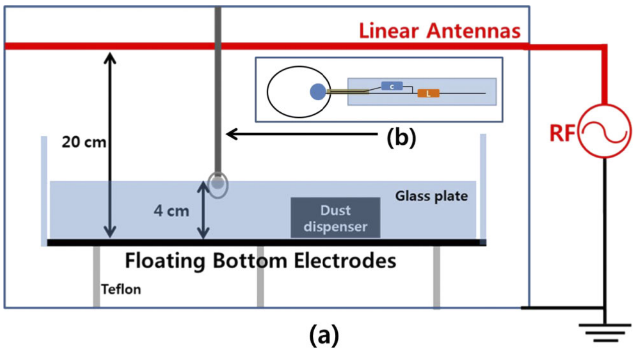

Fig. 1. (a) Experimental setup in the TReD. (b) A planar electric probe with the RF compensation circuitry. The capacitance (100 pF) is C, and L is the ferrite by winding the enamel line, which was specified at 13.56 MHz below −50 dB amplitude.

by the dusts.[8–12] However, experimental demonstrations for the theoretical results are insufficient. This may be because the dust effects are smaller than other variables such as the mixing gas, plasma power, and pressure.[1,2,7,13–15] Also, control of the produced and/or sprayed dust is very difficult depending on variables such as the size, lumps of dust or gas ratio. This leads to the amount of dust in plasma being too little or too much.[7,10,13–15] In this work, we investigate dusty plasma by using a planar electric probe at several vacuum pressures. The charged dust density and its charge are calculated by comparing the dusty helium plasma to that of pure helium plasma. Depending on the degree of increase in the amount of dust, the charged dust density increases with decreasing charge due to depletion of the electrons in the background plasma. Our analysis shows that this charge changes the interaction between the dust and the particles in the background plasma.

II. EXPERIMENT

We produced helium plasma in a large rectangular device, we call the transport and removal experiments of dust (TReD) device whose dimensions are 1200 (L) × 500 (W) × 440 (H) mm consisting of four linear antennas. The bottom electrodes consist of forty-three stainless bars [450 (L) × 28 (W) mm] whose connections to the device wall are floated electrically, as shown in Fig. 1a. RF plasma of 13.56 MHz was launched with 150 watt by the four linear antennas which were connected in parallel. Tungsten dust of 1.89 micron (Fisher Sub-Seive Sizer) were sprayed in the plasma by a dust dispenser made by a commercial speaker (20 watts with 8 Ω) installed in the center of the bottom electrodes. The amount of the sprayed dust was controlled by an increase in the dust dispenser input voltage (DDIV): 150 mV, 200 mV and 300 mV. In order to block dust escaping from the plasma, four glass plates were installed on the edge of the bottom electrodes. The sprayed dust was levitated and spread above the bottom electrodes, where they then constructed a layer. Depending on the increase in the amount of dust, the thickness of the layer was increased, which was checked by the laser scattering detection. A planar electric probe 10 mm in diameter was vertically installed at the center of the TReD device, which was measured 4 cm from the bottom electrodes. The probe had a RF compensation circuitry consisting of a ferrite by winding the enamel line that was specified at 13.56 MHz below −50 dB amplitude, as shown in Fig. 1b. In order to maintain the same conditions for each experiment, the operating time of the DDIV and the acquiring time of the electric probe signal were kept equally.

III. RESULTS AND DISCUSSION

Figure 2 shows the current-voltage (I-V) curves at 10 mtorr. The electron current decreases with increasing amount of dust (increasing the DDIV). This indicates that the electrons attach to the dust because the velocity of the electron is faster than that of the heavier ions. We assume that the entire amount of the reduced electron density attaches to the dust grains.[15] The dust is negatively charged by the electron attachment, and they can play the role of negative ions.[15] At this time, the ion current can decrease for keeping to quasi-neutrality in the plasma because the plasma losses are produced by depletion of the electrons.[7] In addition, the ion density in the background plasma can be changed by the negatively charged dust, which can absorb and/or trap the ions.[9,11,12]

The macroscopic neutrality for the dusty plasma is determined by[8]

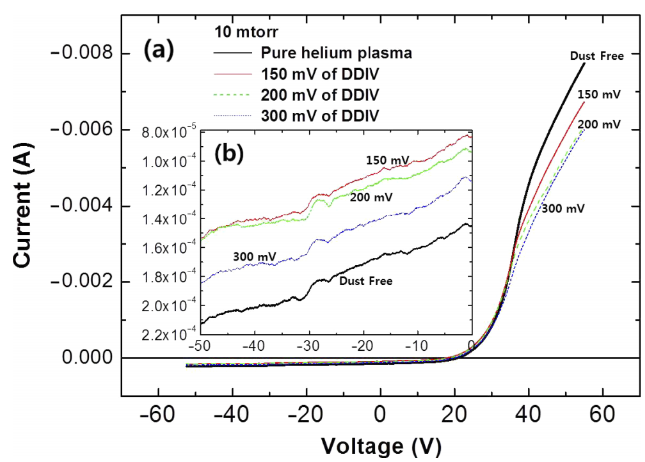

Fig. 2. (a) Current-voltage (I-V) curves at 10 mtorr with an increase in the DDIV. (b) Extended ion saturation currents.

$$n_i = n_e + \frac{Q}{e} N_d \ , \tag{1}$$

where n_i is the ion density, n_e is the electron density, e is the electron charge, Q is the charge on the surface of the dust and N_d is the charged dust density. If the dusts are spherical in shape,[8] the charge (Q) on the dust is determined by[7,14,15]

$$Q = 4\pi\varepsilon_0 a V_s \ , \tag{2}$$

where ε_0 is the permittivity, a is the radius of the dust, and V_s is the dust surface potential.

Figure 3 shows the charged dust density (N_d) and the charge (Q) at 150 mV of the DDIV. The charged dust density increases and the charge decreases with increasing operating pressures. This means that the charged dust density is mainly affected by the particle density in the background plasma.

Figure 4a shows the charged dust density (N_d) and the charge on dust at 10 mtorr with the increasing amount of dust. The charged dust density increases with decreasing charge due to depletion of the electrons in the background plasma.[7] The charge is the charged potential that is proportional by Eq. (2), which is affected by the amount of dust. The charge can change the interactions between dust and particles in the background plasma.[9,11,12] Figure 4b shows the dust effect on the background plasma with the increasing amount of dust. The electron density decreases linearly. The ion densities in the dusty plasma are smaller than that of the pure plasma. The ion density increases with the increasing amount of dust compared to the lowest ion density, which is 150 mV of the DDIV. The decrease of the ion density can be considered as the loss of plasma[7] for keeping the quasi-neutrality property and collecting the force of the charged potential.[9,11,12] The plasma experiences depletion of the electrons with an increase in the amount of dust because the electrons attach to the dust. In order to keep the quasi-neutrality, the efficiency of the producing plasma can be decreased by neutralizing the ions in the background plasma.[7] Furthermore, when the amount of dust is low, the dust can be strongly negatively charged by having enough electrons.[7,11,12] The strongly negatively charged dust can collect the ions by the charged potential.[11,12] The strongly negatively charged dusts can be neutralized and/or weakly negatively charged by absorbing the ions.[11,12] Therefore, the ion density in the background plasma decreases at low dust quantity.

These effects are directly analyzed by the ratio (η) of the ion and the electron saturation current from the I-V probe curves determined by[15]

$$\eta = \frac{I_{es-d}/I_{es-0}}{I_{is-d}/I_{is-0}} = \frac{n_e}{n_i} \ , \tag{3}$$

where I_{es} is the electron saturation current, I_{is} is the ion saturation current, subscript 0 is the pure helium plasma and d is the dusty helium plasma.

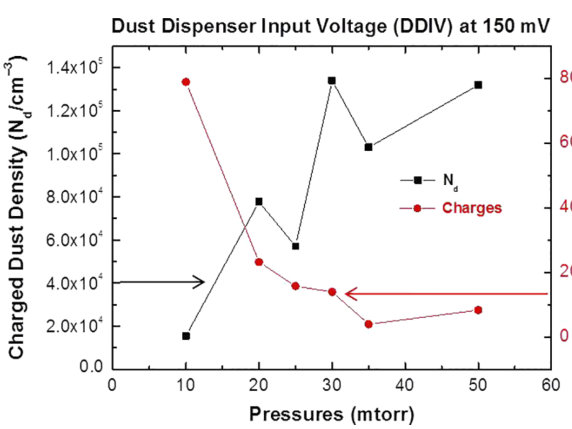

Fig. 3. Charged dust density and the charge on the surface of the dust with an increase in the operating pressure. The DDIV is at 150 mV.

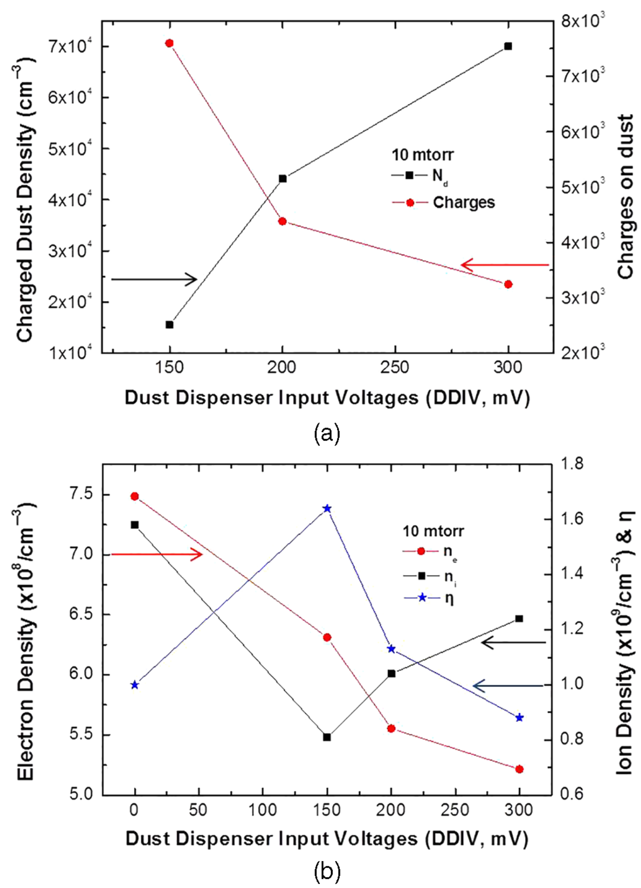

Fig. 4. (a) Charged dust density and the charge on the surface of the dust with an increase in the DDIV. (b) Electron density, ion density and ratio (η) of the electron to ion saturation current. The ratio (η) is the ratio of the electron density to the ion density.

The η is the direct ratio of the electron density to the ion density in the background plasma, and the reference value is 1 for pure helium plasma. The value of η can distinguish the interaction between the dust and the ions in the background plasma. The η value is 1.64 at 150 mV, 1.13 at 200 mV and 0.88 at 300 mV. This value exceeds the reference value 1 until the 200 mV of the DDIV and is below the reference value 1 at 300 mV of the DDIV. When the amount of dust is low, the dusts are strongly negatively charged by sufficient electron attachment, which can absorb the ions ($\eta > 1$). Therefore, the ion density decreases. When the amount of dust is high, the dust is weakly negatively charged by depletion of the electrons. This means that the forces collecting the ions decrease ($\eta < 1$). Therefore, the ion density is higher than 150 mV of the DDIV.

IV. CONCLUSIONS

We investigated 13.56 MHz helium dusty plasmas by using a planar electric probe in a large-scale device by increasing the amount of dust. The charged dust density and the charge were calculated by comparing the dusty helium plasma to that of the pure helium plasma. When the dust is contained in the plasma, it is negatively charged due to electron attachment, so the charged dust affects the particles in the background plasma. When the amount of dust is low, the dusts are strongly negatively charged due to sufficient electron attachment, which then absorb the ions. Depending on the increase in the amount of dust, the charged dust density increases with the decrease in the charge due to depletion of the electrons in the background plasma. The charge on the surface of dust is affected by the amount of dust. We analyze the charged dust density and its effect on particles in the background plasma. The results show that the charge change the interactions between the dust and the particles in the background plasma.

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