

Spatial Characterization of Oxygen Negative Ions in Afterglow of an Inductively Coupled Plasma

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Spatial profile of oxygen negative ions produced during the afterglow phase of an inductively coupled radio-frequency (RF) plasma is experimentally investigated, motivated by the development of a gridded ion thruster incorporating both positive and negative ion sources. It is found that the negative ion density exhibits a peak approximately 40–100 mm downstream of the inductive plasma source, depending on the working gas pressure. It is presented that the axial profile of the negative ions in the afterglow mimics the plasma density profile observed during the RF-ON phase, in which the peak of the positive ion density is formed downstream of the source exit as a result of charge exchange collisions of spontaneously accelerated positive ions.

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Gridded ion thrusters (GITs) have successfully been used as propulsion devices of satellites and spacecraft. In conventional GITs, thrust is generated by ejecting a positive ion beam accelerated using electrostatic grids. To maintain charge neutrality of the spacecraft, electrons with a flux equal to that of the ion beam have to be emitted from the system; otherwise, electric fields pulling back the ions to the spacecraft would develop. Therefore, an electron emitter, known as a neutralizer, is essential for the operation of a GIT. Since the momentum of electrons is generally much smaller than that of the positive ions because of their small mass, the electrons do not make a significant contribution to thrust, while the neutralizer consumes non-negligible amount of electric power. A few experiments have been conducted to explore the use of negative ions for neutralization and additional thrust generation [1, 2].

Previous experiments using radiofrequency (RF) plasmas in oxygen have shown that negative ions are efficiently produced during the low-temperature afterglow (i.e., RF-OFF) phase [3, 4], whereas positive ions are the dominant species during the discharge (i.e., RF-ON) phase. One possible thruster concept utilizing negative ions is alternating extractions of positive and negative ions from two independently pulsed RF plasma sources, where the former and latter are produced in RF-ON and RF-OFF phases, respectively. Since the flux of negative ions near the extraction grids dominates the ion beam current, the spatial profile of the negative ion density is one of the key parameters for thruster development. Here the spatial profile of the oxygen negative ions in the afterglow phase

is experimentally investigated, revealing the formation of a density peak downstream of the inductively coupled plasma source.

Experiments are performed using a simple inductively coupled plasma source shown in Fig. 1(a), consisting of a 30-mm-diameter and 150-mm-long quartz tube. The source is attached to a 150-mm-diameter and 600-mm-long diffusion chamber evacuated by a turbomolecular pump, where $z = 0$ is defined as the open-source exit. Oxygen or argon is introduced from the upstream gas injection port via a mass flow controller, and the chamber pressure is measured by a Baratron gauge connected to the diffusion chamber. A double-turn RF loop antenna wound around the source tube at $z = -130$ mm is powered by an automatically controlled frequency-tunable RF generator in the range of 40 ± 3 MHz [5], producing the oxygen plasma. The RF power is set to 40 W.

Figure 1(b) shows typical I - V characteristics of the Langmuir probe in the afterglow phase (100 μ sec after turning off the RF power) for argon and oxygen plasmas. The magnitude of the current for positive bias is much larger than that for negative bias in argon, whereas similar magnitudes of current are detected for both biases in oxygen. This characteristic indicates the production of the negative ions in the oxygen afterglow plasma. To discuss the ion densities, the positive ($I_{\text{sat}+}$) and negative ($I_{\text{sat}-}$) saturation currents, measured at bias voltages of -60 and 80 V, respectively, are used in the present study. It is known that the current ratio $I_{\text{sat}-}/I_{\text{sat}+}$ gives the density ratio α of negative ions to positive ions as [6]

$$\alpha = \frac{n_-}{n_+} = 1 - \frac{1}{\beta} \frac{I_{\text{sat}-}}{I_{\text{sat}+}} \sqrt{\frac{m_e}{M_+}}, \quad (1)$$

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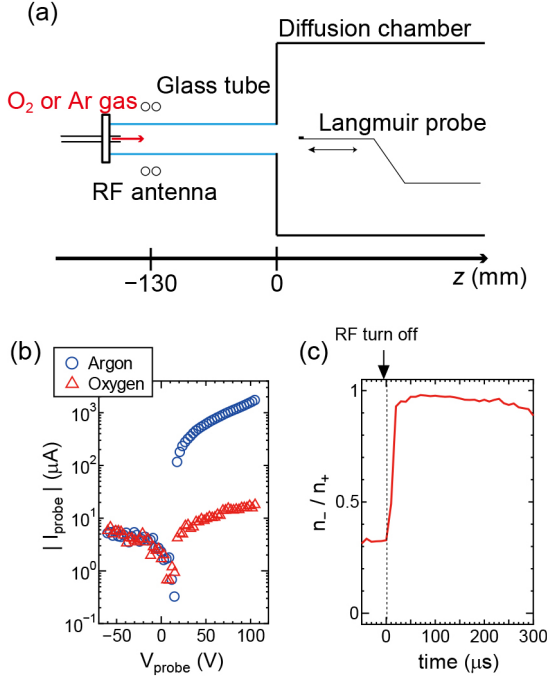


Fig. 1. (a) Experimental setup. (b) I-V characteristics of the LP at 100 μ s after turning off the RF power in argon (open circles) and oxygen (open triangles). (c) Temporal evolution of the density ratio of negative ions to positive ions.

where β is a calibration coefficient determined in an electro-positive argon plasma. Figure 1(c) shows the temporal evolution of α taken for 120 mPa. After turning off the RF power, α close to unity is obtained at $t \sim 50$ μ s, indicating the formation of a nearly pair-ion plasma. This time is slightly changed by the operating gas pressure, and the detailed physical process is not fully understood. In the present study, data at $t = 100$ μ s are used to discuss the spatial profile of the negative ion density.

Figure 2 shows the axial profiles of $I_{\text{sat-}}$ during (a) the afterglow phase and (b) the RF-ON phase for various oxygen pressures. As already described, the majority of the negative charge is due to negative ions in the afterglow phase. In low pressure RF discharge (~ 100 mPa), vibrationally excited molecules are generated by electron impact excitation, enhancing negative ion production via dissociative electron attachment. The negative ion density is primarily determined by the balance between attachment and detachment processes. Global model analysis has indicated that the density ratio (n_{-}/n_{+}) is approximately 0.1 [7]. Therefore, the dominant species of negative charge is the electron. As seen in Fig. 2(a), $I_{\text{sat-}}$ corresponding to the negative ion density exhibits a peak at $z \sim 40$ – 100 mm, and the peak position is observed to shift toward the source exit as the gas pressure is increased. Similar peaks of $I_{\text{sat-}}$ corresponding to the electron current in the RF-ON phase can also be seen in Fig. 2(b). These results demonstrate that the spatial profile of the negative ions in the afterglow phase mimics that of the electrons in the RF-ON phase, which serves as seeds for negative ions generated via the electron attachment process. Therefore, it is critical to understand the

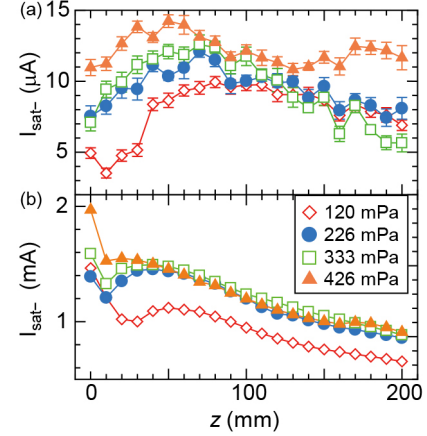


Fig. 2. Axial profiles of $I_{\text{sat-}}$ under different oxygen gas pressures during (a) the afterglow phase and (b) the RF-ON phase.

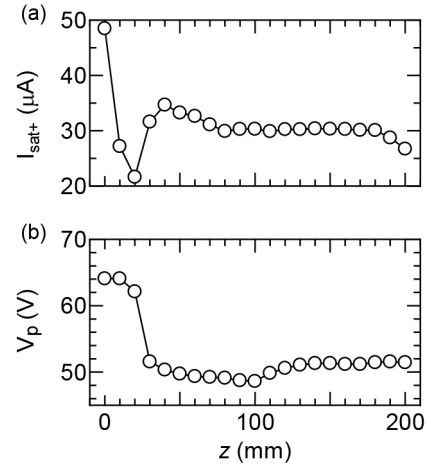


Fig. 3. Axial profiles of (a) $I_{\text{sat+}}$ and (b) V_p during the RF-ON phase in the oxygen plasma for the gas pressure of 120 mPa.

formation mechanism of the plasma density peak in the RF-ON phase.

Figure 3 shows the axial profiles of (a) $I_{\text{sat+}}$ and (b) the plasma potential V_p measured at an oxygen pressure of 120 mPa during the RF-ON phase. The rapid decay of $I_{\text{sat+}}$ near the source exit ($z = 0$ – 20 mm) is observed in Fig. 3(a), while a peak of $I_{\text{sat+}}$ is detected at $z \sim 30$ – 50 mm, which is consistent with the density peak observed in Fig. 2(b). V_p in Fig. 3(b) shows a rapid potential drop near the source exit, which is very similar to previous observation in argon [8], accelerating the positive ions. As the mean free path of charge exchange collisions is approximately 40 mm for a cross section of 10^{-18} m² [9], the accelerated positive ions are converted into thermal ions, reducing their velocity. The reduction of the velocity can explain the formation of the plasma-density peak according to the flux conservation's law [10]. This interpretation is supported by the fact that the mean free path is very close to the distance between the source exit ($z = 0$) and the density peak ($z \sim 50$ mm). It is obvious that the mean free path for the charge exchange collision decreases with increasing gas pressure. Therefore, the axial shift of the density peaks in

Figs. 2(a) and (b) can also be explained by ion acceleration due to the potential drop and subsequent deceleration caused by charge exchange collisions in the diffusion chamber.

Here, the attainable current density of a negative ion beam is discussed with respect to its application to a GIT. Assuming that the current to a beam extraction grid is dominated by the Bohm flux, the current would be briefly equivalent to the Langmuir probe current. The simply estimated current density for a current of 10 μA is about 1.5 A/m². However, in the case of Langmuir probe, the sheath would expand when the probe is biased [11, 12], which may cause an overestimation of the current density. Therefore, a beam extraction experiment will be required in future studies.

In summary, the spatial profile of the negative ion density produced during the afterglow phase of the oxygen RF plasma is experimentally investigated. The results show that the peak of the negative ion density is formed downstream of the RF plasma source. It is demonstrated that this peak formation is correlated with the plasma density profile during the RF-ON phase, where the dominant charge species are electrons and positive ions. The formation of the plasma density

peak during the RF-ON phase can be well explained by the spontaneous acceleration of ions from the source and their subsequent deceleration via charge exchange processes.

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