

# Effect of a Magnetic Filter Across the Exit Hole of a Flat Oxygen Plasma Source

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This study aims to develop a novel flat oxygen plasma source containing a magnetic filter. The aspect ratio of the diameter to the length of the source vessel was approximately four. A pair of small permanent magnets was inserted in a metal flange to generate the magnetic filter at the exit hole of the plasma source. Measured current-voltage characteristics indicated that a clear decrease in the electron temperature was successfully attained across the magnetic filter, which was adequate for producing negative oxygen ions via dissociative electron attachment.

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Currently, the manufacturing of assembled semiconductor process equipment demands a technique that realizes the use of uniform ultrathin films and three-dimensional nanoscale fabrication at a low temperature. Therefore, achieving this using a low-temperature plasma has attracted a significant amount of attention [1]. However, it is still difficult to accurately control the flux of reactive particle species on nanoscale, owing to its inherent fluctuations in temperature and density [2]. Therefore a novel plasma processing is required.

By attaching one electron, oxygen can become a negative oxygen ( $O^-$ ) ion, which is an anion radical. Several reports have indicated that  $O^-$  ions cause strong oxidation in comparison with positive oxygen ions [3]. A recent study on plasma processing using an oxygen plasma suggested that the  $O^-$  ions may play a key role in proceeding oxidation [4]. However, the details are still unclear. For example, the dependence of the amount of  $O^-$  flux and temperature on the oxidation has not been systematically investigated because there are several other kinds of reactive species besides  $O^-$  ions in oxygen plasmas [4, 5].

Oxygen plasmas containing  $O^-$  ions can be produced via several discharge methods [4–7]. However, till date, no such experiment, wherein only  $O^-$  ions are extracted from an ICP oxygen plasma and then reacts with a target has been performed. This is crucial to clearly answer the questions on how oxidation proceeds and what conditions are required to enhance the oxidation using  $O^-$  ions. To address these questions, we have been constructing a new experimental apparatus that will serve as a novel method for producing  $O^-$  ions. In the proposed system, after discharg-

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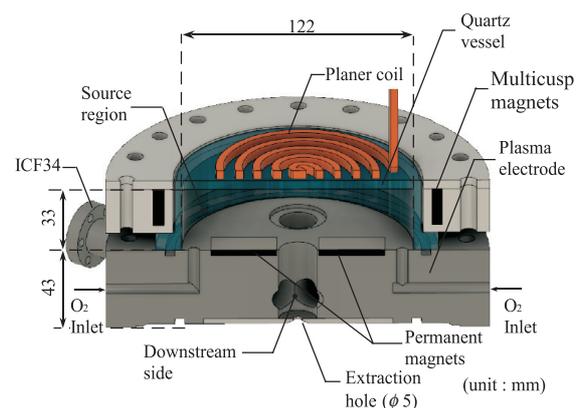


Fig. 1 Schematic of the source region.

ing oxygen gas using a pulsed radio frequency (RF) of a 13.56 MHz that flows in a non-resonant inductive planer coil,  $O^-$  ions are produced via a magnetic filter installed in an exit hole of the plasma source. Herein, we describe the structure of the plasma source and initial data on the electron temperature.

Figure 1 shows a schematic of the negative oxygen ion source. The source is made of a quartz vessel. To obtain a large area where the plasma density is uniform, the length and diameter of the vessel were 33 and 122 mm, respectively. The aspect ratio of the diameter to the length is thus approximately four, which is relatively large. The vessel is evacuated using a turbo molecular pump. The typical pressure before fueling oxygen gas is  $8 \times 10^{-4}$  Pa. As mentioned, oxygen plasma is inductively produced using the RF method. The duration of the RF current applied to the

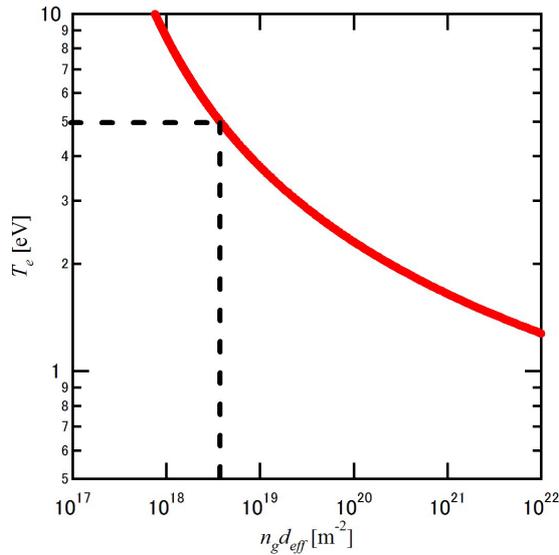


Fig. 2 Dependence of  $T_e$  on  $n_g d_{eff}$  in oxygen plasmas based from a global model.

planar coil was set as 1 s for this experiment. Subsequently, the RF current was turned off for 2 s to keep the vacuum pressure in the adjacent transport region almost constant ( $\approx 1.3 \times 10^{-4}$  Pa). The duty cycle was thus 1/3. To realize a fast pulse mode, a high-speed pulse valve (Parker Co., VAC-1250) was employed. The typical back pressure of the valve is variable; however, it was maintained at 0.5 MPa. The open time of the valve to inject oxygen gas into the planar vessel is also variable; however, it was set to 5 ms for this experiment. During oxygen injection, the pressure in the vessel increases to  $\sim 1.3$  Pa. Subsequently, the RF current being to immediately flow in the planar coil just after the valve is quickly closed.

The planar coil is mounted facing toward the quartz vessel. Around the vessel, a set of 20 permanent magnets are azimuthally placed to create a cusp magnetic configuration [8]. Each magnet has a magnetic intensity of 1.2 kG. Using these, a recombination loss of electrons on the inner surface of the vessel is alleviated [9]. Regarding the magnetic filter, a pair of permanent magnets is embedded in the metal flange, as shown in Fig. 1, because the atomic mass of oxygen is approximately eight times larger than that of hydrogen. Thus, the strength of the magnetic field is set to be approximately 0.8 kG, which is approximately 13 times stronger than that used for producing negative hydrogen ions [10]. In the source region, the electron temperature  $T_e$  needs to be above 5 eV to produce the metastable oxygen molecules,  $O_2^M$  ( $A\Sigma_u^+$ ,  $A^3\Delta_u$ ,  $c^1\Sigma_u^-$ ) [11]. According to a global discharge model [10],  $T_e$  depends on the neutral gas density  $n_g$ , as shown in Fig. 2, where  $d_{eff}$  is the effective distance [12]. Assuming that only the reaction of  $O_2 + e^- \rightarrow O_2^+ + 2e^-$  occurs in the vessel, the value of  $n_g d_{eff}$  must be lower than  $4 \times 10^{18} \text{ m}^{-2}$ . In this case,  $n_g$  must be lower than  $\approx 10^{20} \text{ m}^{-3}$  for this experiment. This also limits

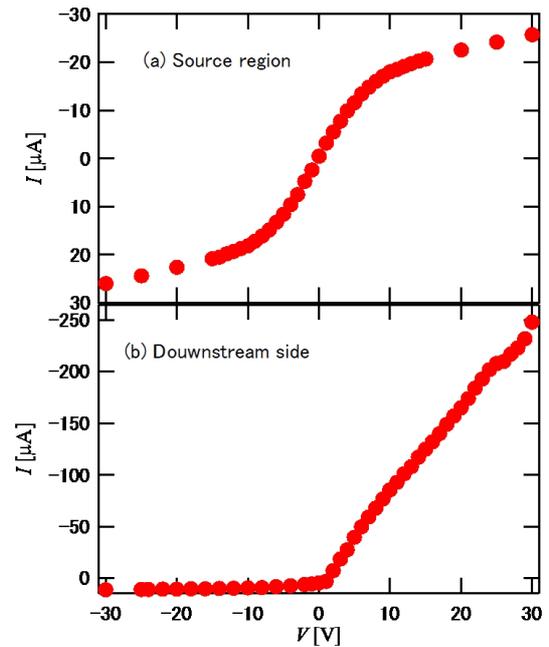


Fig. 3  $I$ - $V$  characteristics measured in (a) the source using a double probe and in (b) the downstream region using a RF-compensated single probe. The RF power is set to be 100 W.

the fueling gas pressure. Beyond the magnetic filter, only the produced  $O_2^M$  and electrons that have lower  $T_e$  values are expected to diffuse through the extraction hole that was made in the metal flange (see also Fig. 1). Actually,  $T_e$  should be below 2 eV [7] to effectively produce  $O^-$  ions via the process of dissociative electron attachment. Then, the produced  $O^-$  ions will be extracted as a beam, which will be reported elsewhere.

In the first series of experiments, current-voltage ( $I$ - $V$ ) characteristics along the machine axis were measured in the source and the downstream region. A double probe was used to measure the  $I$ - $V$  characteristics in the source, 16 mm away from the surface of the plasma electrode, whereas a RF-compensated single probe [13] was employed in the downstream region, 7 mm above the extraction hole (see also Fig. 1). The two cylindrical electrodes of the double probe are made of stainless (SUS304) with a radius and length of 0.5 and 5 mm, respectively. The distance between them was set to be 2 mm. An electrode of the same size as that for the double probe was used for the RF-compensated single probe. Figure 3 shows the preliminary  $I$ - $V$  characteristics measured in (a) the source and in (b) the downstream region. From those data,  $T_e$  and the electron density were calculated to be  $\sim 5$  eV and  $4 \times 10^{15} \text{ m}^{-3}$ , respectively, in the source and 2 eV and  $2 \times 10^{14} \text{ m}^{-3}$ , respectively, in the downstream region. We found for the first time that values of  $T_e$  values satisfy the requirement for producing  $O^-$  ions in the inductively produced plasma in the magnetic filter. In the experiments, the dependence of  $T_e$  on the RF power ( $P_{RF}$ ) was also mea-

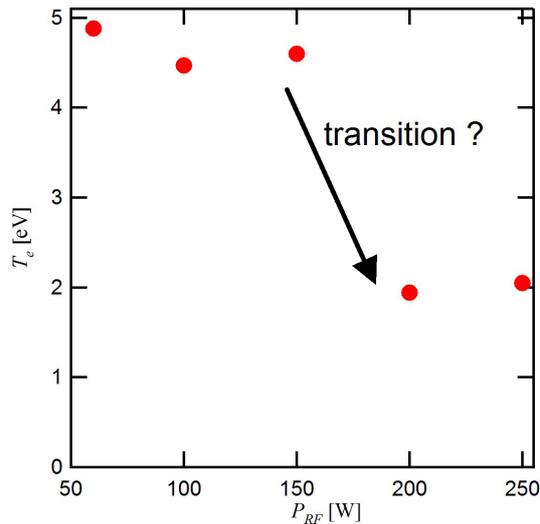


Fig. 4 Dependence of  $T_e$  on  $P_{RF}$  in the source, indicating that  $T_e$  can increase to approximately 5 eV with a  $P_{RF}$  that is below 150 W. In these experiments,  $n_e$  has been inferred to be  $\approx 4 \times 10^{15}$  and  $\approx 1 \times 10^{16} \text{ m}^{-3}$  for cases where  $P_{RF} = 100$  and 250 W, respectively, suggesting that the plasma pressure is kept almost constant as long as  $P_{RF}$  is varied below 250 W.

sured. As shown in Fig. 4,  $T_e$  is  $\sim 5$  eV for cases where  $P_{RF}$  is in the range between 50 and 150 W, which is preferable for producing large amounts of  $\text{O}_2^M$ , as mentioned.

However,  $T_e$  decreases for  $P_{RF} > 150$  W. This possibly reflects a transition from the E- to the H-mode of inductively produced plasmas [14]. The details will be investigated in the next series of experiments.

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