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Time evolution of electronegativity in a pulsed inductively coupled oxygen plasma

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ABSTRACT

The electronegativity in a continuous wave (CW) and pulsed mode plasmas was calculated using the measured results of both the single Langmuir probe and the retarding field analyzer. For the pulsed mode measurement, both of the measurements were performed in a time-resolved method using a boxcar sampling technique. For the conversion of the retarding field analyzer measurement results into absolute positive ion densities, argon plasma was used as a reference. The pulsed oxygen plasma was generated using the inductively coupled antenna and modulated at a repetition rate of 5 kHz and the duty ratio of 50%. The gas pressure was changed from 5 to 30 mTorr. The time evolution of the electronegativity shows that there is a pressure regime where the electron attachment reaction during the RF on-time is very active, indicating that the negative ion density reaches its maximum value during the RF on-time. Compared to the CW oxygen plasma, the electronegativity of the pulsed oxygen plasma varies within a wider range of values.

1. Introduction

Pulsed plasmas have provided powerful process controllability to the process engineers in the semiconductor fabrication industry. This technology has shown the capability to control the composition of radicals in dry etching reactors, which results in better selectivity than in previous performances [1]. Pulsed plasmas have also contributed to reducing the charge accumulations on the substrates so that the plasmas could protect the semiconductor devices from charging damage [2,3]. Moreover, a number of researchers have demonstrated other fluent capabilities of this technique such as improving the etch rate, deposition rate, and even non-uniformity [4–7], which includes almost all the properties needed in processing control.

Many researchers have concentrated on uncovering the physics of pulsed plasmas present behind these powerful performances. However, most of this research has been concentrated on the detailed behaviors of electrons. In those studies, the electron properties in various conditions are known to us and such properties are even measured or simulated in a time-resolved manner so that we can see the detailed behavior of electrons.

However, the characteristics of these pulsed plasmas have not been studied well enough from the viewpoints of ion or reactive species. Several time-resolved measurements and simulations have been tried in the last few decades [8,9], but those results are insufficient to more precisely show how ions and reactive species evolve under the various discharge conditions.

In electropositive plasmas, we could simply expect that electrons and ions are present at the same number of particles at each time, but in electronegative plasmas the situation is fundamentally different. Negative ions start to contribute to the charge neutrality and make the situation very complex. Several studies have revealed the properties of ions using the time-resolved mass spectroscopic method or photo-detachment method [10–13], but, due to their complexity, it is not easy to use them in various conditions. On the other hand, the time-resolved retarding field analyzer method provides a rather simple way to obtain ion properties such as IEDFs (ion energy distribution functions) and a spatial distribution of ion density. Using this rather simple method, we performed the time-resolved IEDF measurement in the pulsed oxygen plasma which is known to have typical electronegative characteristics. In addition to this, the time-resolved single Langmuir probe measurement was also performed to measure the electron properties. Combining these data, we could infer the characteristics of negative ions in the pulsed oxygen plasma. As a representative parameter, we obtained the time evolving electronegativity using the densities of electrons and positive ions.

2. Experimental setup

Fig. 1(a) shows the schematic diagram of this experiment. The vacuum chamber has a cylindrical shape (700 mm in diameter and 250 mm in length) and is made of SUS. The vacuum chamber has a chuck that could place substrates up to 450 mm in size. For the symmetric pumping, there are six (100 mm in diameter) circularly symmetric holes on the bottom plate of the chamber which separates the main chamber volume from the pumping path converging toward the turbo molecular pump. The gas inlet is located on the side of the chamber. The capacitive manometer reads the pressure at the side of the chamber. The chamber has four viewports that are located symmetrically at the chamber side wall, and one of them was used as a

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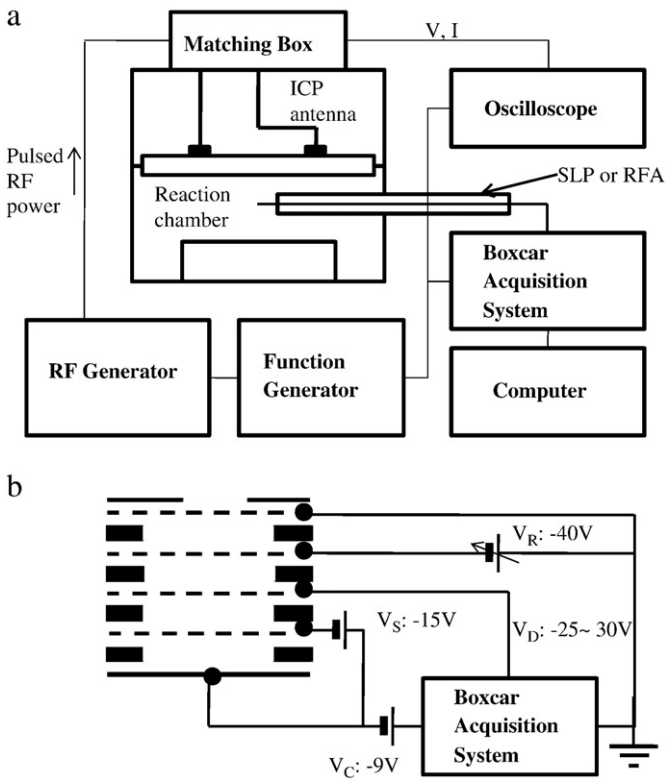

Fig. 1. Schematics of the experimental setup. (a) The vacuum chamber and the RF pulsing system and (b) the retarding field analyzer with the grid voltage ranges.

port for the installation of measurement tools. The alumina plate (670 mm in diameter and 30 mm in thickness) on top of the chamber provides vacuum sealing and roles as a dielectric window for the ICP antenna. The turbo molecular pump has a pumping speed of 500 l/s, and the 500 l/m rotary pump backs the turbo pump. The base pressure of the chamber is under 10^{-5} Torr.

The antenna assembly for the plasma generation has separate two copper coils in concentric configuration. This antenna is produced by PLASMART Company under the name DoSA (Double Stack Antenna) due to its capability of circularly uniform plasma generation. The inner and outer coils have diameters of 180 mm and 450 mm, respectively, and the outer coil was only used in this experiment. The coil is air-cooled by multiple fans for its temperature stability, and the surface of the coil is coated by silver to prevent oxidation while operating for a long time period.

The time-resolved electron density measurement was performed by a single Langmuir probe (SLP) using the boxcar sampling technique. The probe tip was 0.1 mm in diameter and 6 mm in length and made of tungsten. The probe was inserted to the chamber center position through the side of the discharge chamber, which is 100 mm apart from the dielectric window. The RF compensated probe system used in this experiment is described in detail in [14]. The commercial probe system (PLASMART Inc., SLP2000) provides the boxcar sampling function. The time resolution of this method is 100 ns. The trigger signal from the function generator (SRS DS430) was fed into the SLP2000 controller and the RF generator (SEREN R3001, 13.56 MHz) simultaneously. The RF generator can operate in external trigger mode and has a pulse frequency range of up to 10 kHz with a duty ratio range from 10 to 90%. To confirm the coincidence of the phases between the pulsed RF output and the trigger signal, the voltages at the output of the matching box and the trigger signal from the function generator are always compared to each other using the oscilloscope. The repetition rate and the duty ratio were fixed at 5 kHz and 50%, respectively, in this experiment.

Fig. 1(b) shows the structure of the retarding field analyzer (RFA). The configuration is based on the typical four grid system, and the role of each grid is described in detail in [15–17]. All grids have 50 μm holes and 50% transparency and are made of SUS material. The total length of the grid system is around 2.5 mm. The opening diameter in front of the first grid is 3 mm, and the aluminum case enclosing the grid system was cooled by the circulating water to prevent the grids from degrading due to the thermal budget conducted by the operating plasma. To utilize the same boxcar sampling function, the SLP2000 controller was used again, but the electrical paths for the $V_S + V_C$ (for the ion current collection) and V_D (for the ion energy discrimination) are separated from each other by modifying the circuit board inside the controller.

Contrary to the SLP measurement, the RFA measurement can only measure relative densities. To calculate the proper electronegativity, it is necessary to convert the RFA signals into absolute densities. The calibration factors for this conversion were acquired from the CW argon plasma (see Fig. 2). In the argon plasma, there are only electrons and positive ions, so we can expect that the RFA signals are equal to the electron densities measured by the SLP at the same condition, based on the charge neutrality assumption. The calibration factors were calculated for each pressure condition.

3. Results and discussion

The time-resolved measurement result of the electron density in the pulsed oxygen plasma is shown in Fig. 3(a). From 10 to 30 mTorr, the electron densities decrease during the RF on-time and increase during the RF off-time. This is a different tendency with respect to that

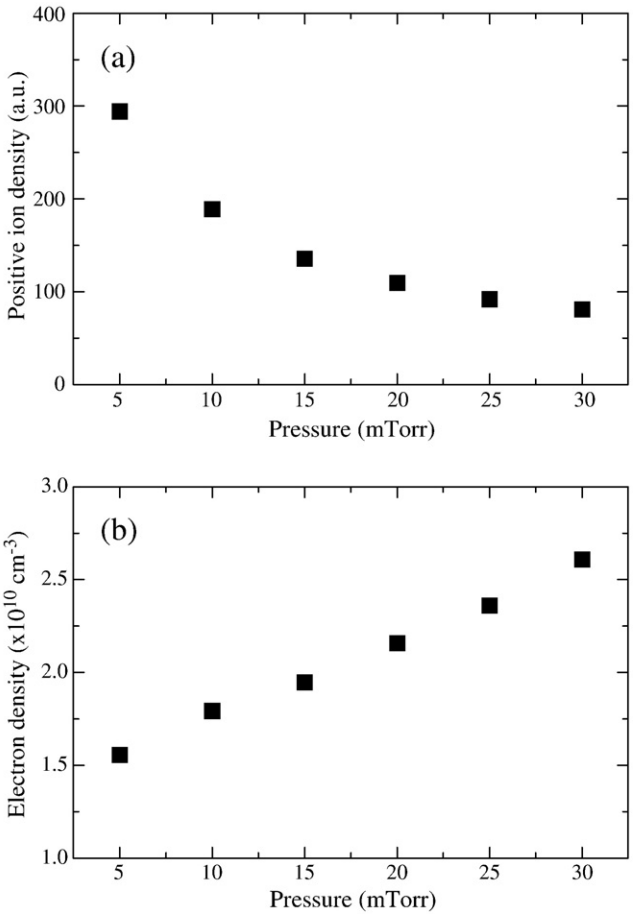

Fig. 2. The electron density and the RFA signals in the CW argon plasma for the conversion of the RFA signals to absolute values. (a) the electron density as the pressure varies. (b) the RFA signals as the pressure varies. The RF power is 500 W.