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Evaluation of the Sheath Factor in Electronegative Gas Plasmas

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Abstract

The influence of the change in the sheath structure on the Langmuir probe characteristics in an electronegative gas plasma was evaluated quantitatively using the reduction rate of the ion saturation current in a SF_6/Ar double plasma. Here, the density ratio of negative ions to positive ions, α, and ion mass were estimated from the phase velocity of the ion acoustic wave and the mass analysis with a quadruple mass spectroscopy (QMS), respectively. It was found that the sheath factor, which represents the change in the sheath structure, increases when $\alpha > 0.6$, and that it agrees qualitatively with the expansion rate of sheath surface area calculated theoretically.

Keywords:

ion sheath, Langmuir probe, SF_6 double plasma, ion acoustic waves

1. Introduction

In fabricating ultra-large-scale-integrated (ULSI) circuits, a variety of reactive gas plasmas, such as SiH_4, O_2, SF_6 and C_4F_8, have been widely used in the chemical vapor deposition (CVD) and etching process. It is well known that these reactive gas plasmas produce much negative ions. Recently, the role of negative ions has attracted much attention; negative ions provide less damage rather than positive ions, since most of their neutralization on the material surface is endothermic [1]. Therefore, in order to get deeper understanding of the mechanism of CVD or etching, it is necessary to measure the negative ion density. Usually, the measurements of the negative ion density have been performed using a laser photodetachment technique [2], the Langmuir probe [3] and the propagation of ion acoustic waves (IAWs) [4]. The Langmuir probe measurements have quite good spatial resolution, although this method of measurement suffers due to sheath problems. A large number of theoretical studies on sheath structure in electronegative gas plasmas have been made [3,5,6]. In general, the potential structure in the ion sheath is never simple, and the ion saturation current is expressed as a complicated function of the density ratio of negative ions to positive ions, α. Thus, a survey on the sheath structure is necessary to understand the physics of the sheath.

In this study, *sheath effects* are quantitatively evaluated taking into account the reduction rate of the ion saturation current in a SF_6/Ar double plasma. Here, a term "sheath effects" represents the influence of changes in the sheath structure and Bohm velocity on the ion saturation current. The reduction of the ion saturation current is due to the decrease of the positive ion density, increase of the positive ion mass, and sheath effects. Therefore, if positive ion mass and density are determined independently, sheath effects can be

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evaluated. Here, the positive ion mass was determined from mass analysis using the quadruple mass spectrometer (QMS) system. The positive ion density was calculated as a sum of the electron density and negative ion density, which were estimated from the Langmuir probe characteristics and the propagation of the ion acoustic wave (fast mode), respectively.

2. Analysis

As the negative ion density increases, a decrease in the ion saturation current is observed [8]. The ion saturation current I_+ is described as follows:

$$I_+ = (1/2) e N_+ S_0 \Omega \sqrt{\kappa T_e / M_+}\ , \tag{1}$$

where N_+, M_+ and S_0 denote the density and mass of positive ions and the geometric probe surface area, respectively. In eq. (1), a factor Ω, called "*sheath factor*" here, is introduced in order to express sheath effects in electronegative gas plasmas. In other words, Ω is a function of α and includes the change rates of sheath surface area, S, and Bohm velocity, u_B:

$$\Omega(\alpha) = \frac{S(\alpha)}{S(\alpha=0)} \frac{u_B(\alpha)}{u_B(\alpha=0)}\ . \tag{2}$$

Note that $\Omega = 1$ when $\alpha = 0$.

In order to evaluate Ω quantitatively, the following equation is useful:

$$\Omega(\alpha) = \frac{I_+(\alpha)}{I_+(\alpha=0)} \frac{N_+(\alpha=0)}{N_+(\alpha)} \sqrt{\frac{M_+(\alpha)}{M_+(\alpha=0)}} \sqrt{\frac{T_e(\alpha=0)}{T_e(\alpha)}} \tag{3}$$

Here, each physical quantity, i.e., T_e, I_+, M_+ and N_+, must be measured. First, T_e and I_+ are determined from the *V–I* curve measured with the planar Langmuir probe. The reduced mass of positive ions M_+ is estimated from the mass spectrum analysis by means of the QMS system using the following equation:

$$1/M_+ = \sum_j I_j / M_{+j}\ , \tag{4}$$

where I_j represents the intensity ratio of j_{th} ion's mass spectrum. Finally, N_+ is calculated from:

$$N_+ = N_e / (1-\alpha) \tag{5}$$

$$N_e = \sqrt{\frac{2\pi m_e}{\kappa T_e}} \frac{I_{es}}{e S_0}\ . \tag{6}$$

Here, the negative ion current is ignored unless $\alpha >$ 0.99, since negative ions have larger mass and lower temperature than electrons.

On the other hand, the negative ion density ratio α is determined from the phase velocity of the ion acoustic wave (fast mode) from the following equation [8]:

$$\frac{\omega}{k} = \sqrt{\frac{1+\alpha/\mu}{1-\alpha}} \sqrt{\frac{\kappa T_e}{M_+}}\ , \tag{7}$$

where k and μ denote the wave number and the mass ratio of negative ions to positive ions, respectively. The mass of negative ions is determined using the same analysis as the one for positive ions. The phase velocity ω/k is determined from the wave patterns obtained by an interferometric method.

3. Experimental Apparatus

The schematic diagram of the experimental setup utilizing a SF_6/Ar double plasma (D.P.) device is shown in ref. [7] in detail. The double plasma device consists of a stainless chamber whose size is 50 cm and 100 cm in diameter and length, respectively. In this experiment, the separation grid was removed such that the chemical composition in the plasma was uniform in whole regions. Argon and SF_6 gases were introduced into the chamber with the mass flow controller separately, the former was kept at 8 sccm which corresponds to neutral gas pressure of 3×10^{-4} Torr, and the latter was regulated from 0 to 0.1 sccm. The accelerating voltage and discharge current was 50 V and 60 mA, respectively. A 0.6 cm-diam planar Langmuir probe was used to measure the plasma parameters and detect the ion acoustic wave. In order to obtain the interferometric wave patterns, a sinusoidal voltage (60 kHz, V_{pp} = 190 mV) was applied to the 8cm-diam mesh grid. Excited waves were detected with the Langmuir probe biased at +9 V, which was movable along the chamber axis using a motor drive system.

4. Results and Discussions

The change in I_+, I_{es} and T_e is plotted in Fig. 1(a) as a function of the SF_6 gas flow rate. A slight increase of T_e is explained as follows [9]; as the negative ions increase, the electron density and consequently the overall ionization rate reduce. Thus, T_e should increase to sustain the same ionization rate. The dominant ions are Ar^+, SF_3^+ and SF_5^+ in positive ions, and F^-, SF_5^- and SF_6^- in negative ions. The reduced ion masses were calculated and is shown in Fig. 1(b). A change in the mass spectrum intensity ratio results in increases in the reduced mass of positive and negative ions. The electron density, N_e, and α are plotted in Fig. 1(c). With a small quantity of SF_6 gas of 0.02 sccm, α reaches more than

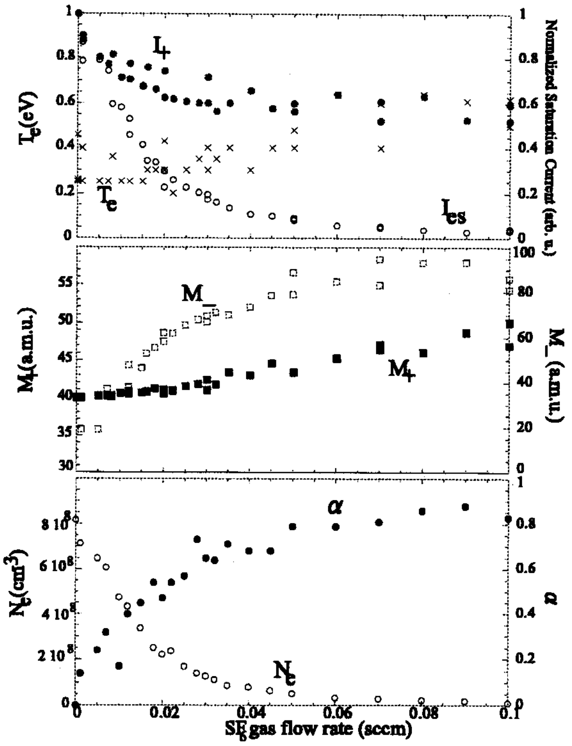

Fig. 1 The dependence of (a) the electron temperature T_e (×), ion saturation current I_+ (●) and electron saturation current I_{es} (○), (b) the positive and negative ion reduced mass determined from the mass spectrum analysis using QMS system and (c) the electron density N_e and the negative ion density ratio α on the SF_6 gas flow rate.

0.6. Finally, the sheath factor Ω is evaluated using eq. (3) and plotted in Fig. 2 with crosses as a function of α. It is found that Ω = 1 until α = 0.6, however, Ω increases exponentially in higher α regions. Therefore, it is concluded that sheath effects become dominant in the region of $\alpha > 0.6$.

Let us explain the increase in Ω where $\alpha > 0.6$. In electronegative gas plasmas, sheath width increases with the increase in α. Shindo and Horiike [6] calculated the change rate of sheath width x_s as a function of α for the case of a planar probe. Here, if it is assumed that a cylindrical-shaped sheath is formed in front of the planar probe surface, as shown in Fig. 2, the change in sheath surface area is proportional to the change rate of x_s. The change rates of x_s calculated by Shindo and Horiike assuming that (t_+, t_-) = (0.05, 0.05) and (0.1, 0.05) are also plotted in Fig. 2 with open and closed circles, respectively, where $t_\pm$ represents the positive and negative ion temperature normalized to T_e. In Fig. 2, no discrepancies are found between x_s with different

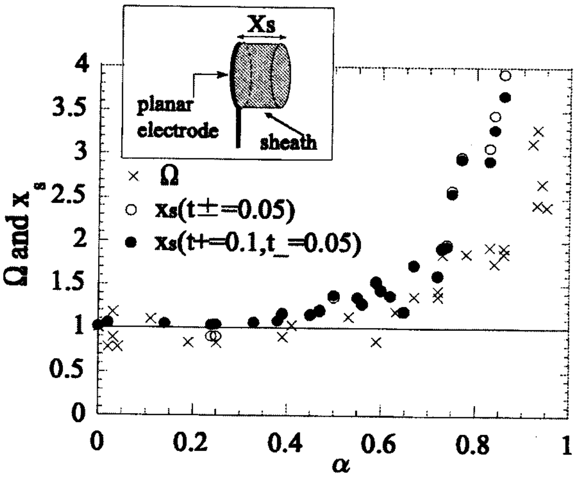

Fig. 2 The dependence of the calculated sheath factor Ω (×) and the expansion rate of sheath surface area for (t_+, t_-) = (0.1, 0.05) (●) and (0.05, 0.05) (○) on the negative ion density ratio α.

temperatures. In addition, the behavior of Ω and x_s shows qualitative agreements. Therefore, it is concluded that the increase in Ω is partly due to the increase in sheath surface area. However, in Fig. 2, some discrepancies between x_s and Ω are found when $\alpha > 0.8$, which is probably due to the change in Bohm velocity, although this was not discussed quantitatively here.

5. Conclusion

Sheath effects were evaluated quantitatively from the simple analysis of the reduction rate of the ion saturation current in a SF_6/Ar double plasma. Here, the ion saturation current and the electron temperature were obtained from the *V–I* curve measured with a planar probe, and the reduced mass of positive ions from the mass spectrum analysis using the QMS. The positive ion density was determined from $N_e/(1 - \alpha)$, where the electron density N_e and the negative ion density ratio α were estimated from the *V–I* curve measured with the probe and the phase velocity of the ion acoustic wave. As a result, Ω was close to unity in $\alpha < 0.6$, while Ω increased in $\alpha > 0.6$. Moreover, an attempt to compare the behavior of Ω with the sheath theory was made. It was found that the increase in Ω was partly due to the expansion of the sheath surface area calculated by Shindo and Horiike [6].

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