Behaviour of sheath voltage in negative ion plasma

J Y Zhang 1, R Ichiki 2 and Y Kawai 3

1 School of Medicine, Dalian University, Dalian, 116622, P. R. China
2 Department of Electrical and Electronic Engineering, Oita University, Oita, 870-1192, Japan
3 Interdisciplinary Graduate School of Engineering Sciences, Kyushu University, Kasuga, Fukuoka, 816-8580, Japan

E-mail: kawai@aees.kyushu-u.ac.jp

Abstract. The sheath voltage in SF6/Xe plasma was measured with the Langmuir probe and compared with the theoretical value calculated from the sheath equation including negative ions. The negative ion density was estimated from the reduction of the electron saturation current. It was found that the observed sheath voltages agree with the theoretical values qualitatively.

1. Introduction

As well known, there are negative ions in reactive plasmas for CVD [1-2]. Negative ions are confined in plasma without diffusing to discharge electrodes, leading to high negative ion density. Therefore, negative ions may play an important role especially in plasma CVD such as the fabrication of amorphous silicon/microcrystalline silicon for thin film silicon solar cells. However, there are almost no reports on the behaviour of negative ions in plasma CVD because of the difficulty of negative ion measurements in reactive plasma. The negative ion density is widely measured utilizing a laser photodetachment technique [3]. The simplest method to estimate the negative ion density is to use the Langmuir probe, that is, the negative ion density normalized to the ion density is easily estimated from the reduction of the electron saturation current [4]. We have proposed the sheath voltage method to estimate dominate ions [5], that is, when both the sheath voltage and the electron temperature are known, we can estimate dominant ion species. Furthermore, when there are negative ions, the sheath voltage decreases and Bohm sheath is modified [6]. Thus, the sheath voltage provides interesting information about negative ions as well as positive ions. In fact, we observed the decreases in the sheath voltage in SF6/Ar double plasma and found that the observed sheath voltages agree with those calculated using the sheath equation including negative ions [5]. Here, in order to establish the sheath voltage methods in negative ion plasma, we performed the experimental on the sheath voltage measurements in SF6/Xe double plasma. The use of Xe gas has an advantage that provides higher electron density plasma, leading high etching rates or high deposition rates.

2. Experimental

The experiments were performed using a double plasma device [7-8], as shown in figure 1. The diameter and length of the stainless vacuum chamber were 500 mm and 1000 mm, respectively. In this experiment, the separation grid (SG) was removed such that the chemical composition in the
plasma was uniform in all regions. Xe and SF$_6$ gases were introduced into the chamber with the mass flow controllers separately. The flow rate of Xe gas was kept at 6 sccm ($8 \times 10^{-4}$ Torr) and that of SF$_6$ gas was regulated from 0 to 0.1 sccm. The double plasma, produced by dc discharges between the filaments (F) and the chamber wall (A), was confined by the multidipole cusp–mirror magnetic field generated by permanent magnets. The accelerating voltage and discharge current were 50 V and 60 mA, respectively. A 0.6-cm-diam planar Langmuir probe (P) was used to measure the plasma parameters. The Langmuir $I-V$ curve was measured with the X-Y recorder (the input impedance: 1 MΩ). The probe surface was cleaned periodically using ion bombardment in pure Xe plasma. Mass spectra of positive and negative ion species were analyzed with the QMS (Hiden EQP-500).

**Figure 1** A schematic of DP machine. Here P and Q denote the Langmuir probe and the QMS.

The negative ion density normalized to the ion density, $n_-/n_+$, was estimated from the following equation [4]:

$$n_-/n_+ = 1 - \frac{I_{es}}{I_{ eso}}$$

(1)

where $I_{es}$ and $I_{ eso}$ is the electron saturation current with negative ions and without negative ions, respectively.

3. Results and discussion

At first a SF$_6$/Xe double plasma was produced and the plasma parameters were measured as a function of SF$_6$/(Xe+SF$_6$) with the Langmuir probe, where the ratio SF$_6$/(Xe+SF$_6$) is that of the mass flow rate. The plasma parameters were: $T_e=0.09-0.2$ eV and $n_+ \sim 3.9 \times 10^{14-15}$ m$^{-3}$. The QMS spectra showed that dominant positive ions and negative ions are Xe$^+$ and F$, respectively. When SF$_6$/(Xe+SF$_6$) was increased, the electron saturation current rapidly decreased. We estimated the negative ion density normalized to the ion density, $n_-/n_+$, as a function of
SF6/(Xe+SF6) from Eq. (1). Figure 2 shows that when SF6/(Xe+SF6) is increased, the negative ion concentration rapidly increases.

**Figure 2** The dependence of the negative ion concentration n−/n+ on SF6/(Xe+SF6). Here the curve was plotted to fit the experimental results using the least-squares analysis.

Then, we measured the sheath voltage as a function of SF6/(Xe+SF6) and plotted the sheath voltage as a function of negative ion concentration n−/n+ in figure 3. Here the sheath voltage was estimated from the potential difference between the plasma potential and the floating potential that were measured with the probe. The solid line in figure 3 is the theoretical sheath voltage that was calculated using the sheath equation derived by Shindo and Horiike [9]. The sheath equation and the Bohm criterion voltage $V_B$ are as follows:

\[ n_e \exp\left(-\frac{eV}{kT_e}\right) \left(\frac{kT_e}{2\pi n}\right)^{1/2} + n_- \exp\left(-\frac{eV}{kT_-}\right) \left(\frac{kT_-}{2\pi M_-}\right)^{1/2} = \]

\[ \left\{ \frac{2(kT_e + eV_B)}{M_+} \right\}^{1/2} \left\{ n_e \exp\left(-\frac{eV_B}{kT_e}\right) + n_- \exp\left(-\frac{eV_B}{kT_-}\right) \right\} \]  

(2)

\[ n_e \exp\left(-\frac{eV_B}{kT_e}\right) \left\{ \frac{1}{kT_e} - \frac{1}{2(kT_e + eV_B)} \right\} + n_- \exp\left(-\frac{eV_B}{kT_-}\right) \left\{ \frac{1}{kT_-} - \frac{1}{2(kT_e + eV_B)} \right\} = 0 \]

(3)
Here M is negative ion mass and $T_+$ and $T_-$ is the temperature of positive ions and negative ions, respectively. As described in Ref. [9], the sheath voltage is very sensitive to $T_+$ and $T_-$. In this calculation, $T_+=T_-$ was assumed and the result of figure 4 was used. As seen from figure 3, the observed sheath voltages agrees with the theoretical ones for $T_-=0.03$ eV except for high negative ion concentrations. One of the reasons for this deviation may be due to the assumption of $T_+$ and $T_-$. Although we did not measure $T_+$ and $T_-$, assumed ion temperature $T_-=0.03$ eV is reasonable since $T_e$ is lower than 0.2 eV.

Figure 3 The dependence of the sheath voltage on the negative ion concentration $n_-/n_+$, where the curves are the theoretical values calculated from the sheath equation, Eqs.(2) and (3).

When there are negative ions in plasma, the ion saturation current decreases because the sheath width broadens out [10]. We plotted the ion saturation current $I_s$ as a function of negative ion concentration. Figure 4 indicates that the ion saturation current decreases proportional to $n_-/n_+$. This tendency was shown numerically by Shindo and Horiike [10]. However, measured ion saturation currents did not agree with the theoretical values. Moreover, the sheath equation is a nonlinear equation, so that there are many solutions [9]. In fact, three solutions existed in SF$_6$/Ar plasma, and the experimental values agreed with the calculated ones. However, as seen in fig. 3, there is one solution for the present parameter region in SF$_6$/Xe plasma. Thus, more detailed discussions about the sheath structure in a negative ion plasma will be necessary for the comparison between the experiment and the theory.
Figure 4 The dependence of the ion saturation current on the negative ion concentration $n_{-}/n_{+}$. Here the curve was plotted to fit the experimental results using the least-squares analysis.

4. Conclusion

We produced a SF$_6$/Xe double plasma to study the characteristics of a negative ion plasma with the Langmuir probe. Here the negative ion concentration was estimated from the reduction of the electron saturation current. It was found that measured sheath voltages agree with the theoretical values for $T_{e}=0.03$ eV qualitatively and the ion saturation current decreases proportional to the negative ion concentration.

References

[1] Matsuda A and Tanaka K 1982 *Thin Solid Films*, 92 171
[2] Lieberman M A and Lichtenberg A J 1994 *Principle of Plasma Discharges and Materials Processing*, Chap.6 (John Wiley & Sons, Inc.)
[3] Bacal M, Hamilton G W, Bruneteau A M and Doucet H J 1979 *Rev. Sci. Instrum.*, 50 2288
[4] Ichiki R, Yoshimura S, Watanabe T, Nakamura Y, and Kawai Y 2002 *Phys. Plasmas*, 9 4481
[5] Zhang J Y, Ichiki R and Kawai Y 2012 *Proc. of XXI Europhysics Conference on the Atomic and Molecular Physics of Ionized Gases (Porto)* P1.5.1
[6] Amemiya H 1990 *J. Phys.D:Appl.Phys.*, 23 999
[7] Shindo M, Uchino S, Ichiki R and Kawai Y 2001 *Rev. Sci. Instrum.*, 72 2288
[8] Fukumasa, Hosoda M and Naito H 1992 *Rev. Sci. Instrum.*, 63 2696
[9] Shindo H and Horiike Y 1991 *Jpn. J. Appl. Phys.*, 30 161
[10] Shindo H and Horiike Y 1993 *Jpn. J. Appl. Phys.*, 32 5109