# Observation of the Electric Field Structure in the Sheath of Electronegative Plasmas by Laser-Induced Fluorescence-Dip Spectroscopy

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We have measured the distribution of the electric field in the sheath formed between electronegative Ar/$SF_6$ plasmas and a biased electrode by laser-induced fluorescence-dip spectroscopy. It has been found for the first time that the electric field in the sheath of an electronegative plasma has a multistage structure, which may be due to the reflections of negative ions and electrons at different distances from the electrode surface.

**Keywords:**

sheath, electric field, electronegative plasmas, laser-induced fluorescence-dip spectroscopy

Electronegative plasmas are widely used in the plasma processing of materials. Since bombardment of material surfaces with ions plays essential roles in many kinds of plasma processing, the understanding of the structure of the electric field in the sheath of electronegative plasmas is an important issue. To date, many theoretical and experimental approaches have been attempted in order to clarify the electric field structure in the sheath of electronegative plasmas. However, because of the lack of reliable experiments achieving sufficient resolution and sensitivity, the precise sheath structure of electronegative plasmas is still an open question. In the present study, we have measured the distribution of the electric field in the sheath formed between electronegative Ar/$SF_6$ plasmas and a biased electrode. This measurement was possible by making use of the fine spatial resolution and the high sensitivity of laser-induced fluorescence-dip spectroscopy of Ar [1].

The experimental apparatus used was the same as that reported previously [2]. A planar electrode biased at –20 V with respect to the ground potential was inserted in an inductively-coupled plasma source. The distribution of the electric field was measured by moving the position of the biased electrode. The discharge gas was a mixture of Ar and $SF_6$, and the degree of electronegativity was controlled by changing the partial pressure of $SF_6$. Laser-induced fluorescence-dip (LIF-dip) spectroscopy [3] employed two tunable lasers (a dye laser and an optical parametric oscillator) to excite metastable ($4s[3/2]^o_2$) Ar atoms to Rydberg states. The Stark effects induced by an electric field cause variations in the spectra of the Rydberg states. We deduced the electric field by measuring the Rydberg states spectra by LIF-dip spectroscopy. The spatial resolution and the sensitivity were 0.2 mm and 3 V/cm, respectively. The details of LIF-dip spectroscopy have been described previously [1]. We measured the electron density $n_e$ using a plasma absorption [4] at several discharge conditions. For the measurement of the ratio of the negative ion density to the electron density (denoted by $\alpha$), we employed laser photodetachment assisted by a Langmuir probe. The plasma potential was measured using a Langmuir probe, and was +23 V with respect to the ground potential in a pure Ar plasma.

The distributions of the electric field observed at various discharge conditions are shown in Fig. 1. The horizontal axis is the distance $z$ from the electrode surface. The values of $n_e$ and $\alpha$ have been identified at the discharge conditions shown in Fig. 1(a) ($n_e = 2 \times 10^9$ cm$^{-3}$ and $\alpha = 0$), Fig. 1(b) ($n_e = 1 \times 10^9$ cm$^{-3}$ and $\alpha = 11$), and Fig. 1(d) ($n_e = 7 \times 10^8$ cm$^{-3}$ and $\alpha = 25$). As reported previously [2], both the magnitude and the distribution of the electric field observed in the case without the addition of $SF_6$ (Fig. 1(a)) was fairly consistent with the result of theoretical calculation based on a fluid model [5]. As shown in Fig. 1(b), the addition of $SF_6$ at 4%, which corresponded to $\alpha = 11$, resulted in a considerable change in the electric field distribution. It is known from the close observation of Fig. 1(b) that there is a small jump in the distribution of the electric field at $z \simeq 2.6$ mm. The jump in the electric field distribution is seen more clearly in Fig. 1(c), where the partial percentage of $SF_6$ was 6%. The decay of the electric field in $0.8 \le z \le 2.2$ mm shown in Fig. 1(c) was more gentle than that shown in Fig. 1(b). At an $SF_6$ percentage of 8% corresponding to $\alpha = 25$, the electric field in $0.6 \le z \le 2$ mm was almost uniform as shown in Fig. 1(d).

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At an $SF_6$ percentage of 10%, as shown in Fig. 1(e), we observed a steep decay in the electric field in $0 \le z \le 0.5$ mm, which was followed by an almost uniform electric field in $0.5 \le z \le 2.4$ mm. After that, the electric field decayed suddenly at $z \simeq 2.6$ mm.

The multistage structure of the electric field distribution shown in Fig. 1(e) can be explained qualitatively by the reflections of negative ions and electrons at different distances from the electrode surface. It is known that the modified form of the Bohm criterion for forming a stable sheath in an electronegative plasma is given by

$$u_s \ge \sqrt{\frac{1+\alpha_s}{1+\gamma\alpha_s}}\sqrt{\frac{kT_e}{M}}\,, \qquad (1)$$

where $u_s$ is the critical speed of positive ions at the sheath edge, $M$ is the effective mass of positive ions, $k$ is the Boltzmann constant, $T_e$ is the electron temperature, $\gamma$ is the electron/negative-ion temperature ratio ($T_e/T_-$), and $\alpha_s$ is the value of $\alpha$ at the sheath edge [6]. Hence the critical speed $u_s$ in an electronegative plasma is slower than that in an electropositive plasma, provided that the electron temperature is the same. The jump in the electric field at $z \simeq 2.6$ mm in Fig. 1(e) is attributed to the reflection of negative ions at the position where the speed of positive ions reaches the critical speed in the electronegative plasma. After the reflection of negative ions, the speed of positive ions becomes slower than the critical speed since charged species are composed of only positive ions and electrons. This is the reason for the almost uniform electric field in $0.5 \le z \le 2.4$ mm. When the speed of positive ions reaches the critical speed in the electropositive plasma, the reflection of electrons occurs, resulting in the strong electric field in $0 \le z \le 0.5$ mm. Further quantitative investigation is necessary in order to understand the multistage structure of the electric field distribution.

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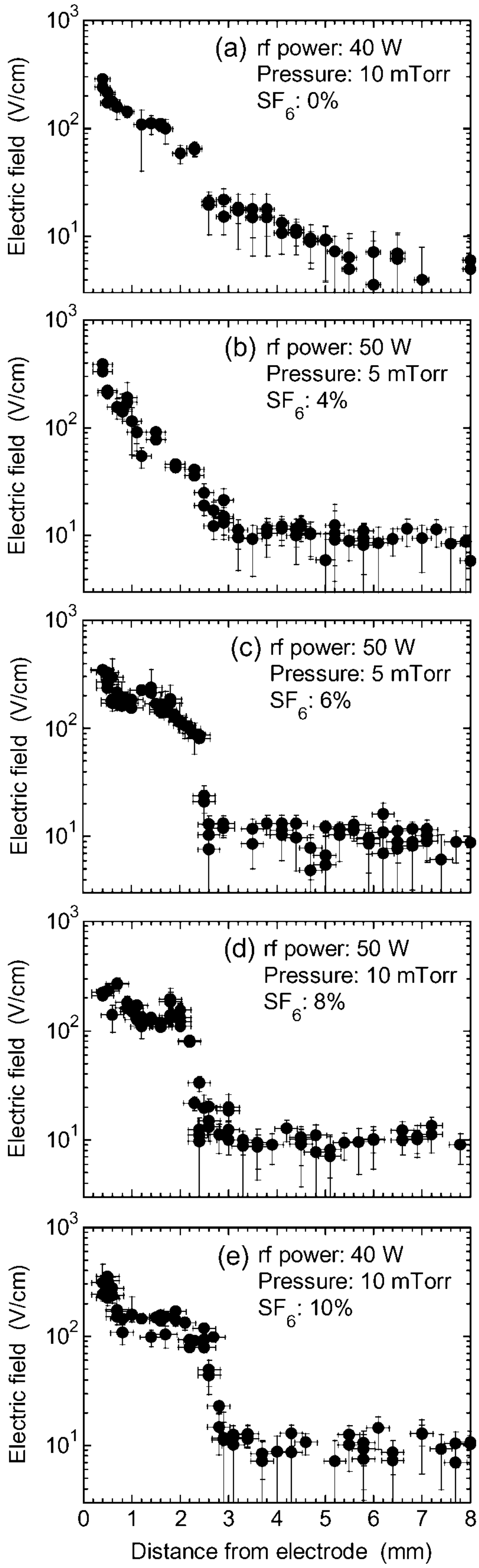


Fig. 1 Distributions of electric field measured at various percentages of $SF_6$ in $Ar/SF_6$ inductively-coupled plasmas.